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Final Technical Report
August 1978

EXPANDED WCCM RANGING CAPABILITY

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Approved for public release; distribution unlimited.

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This report describes the software programs developed by Pattern Analysis and Recognition Corp. for implementing the Wideband Command and Control Modems Automated Test System (WCCM ATS) as an operational data link system in support of the Multilateration Radar Surveillance and Strike System (MRS3) program at RADC. Section one outlines the objectives and characteristics of the test system. The second section provides a functional description of the software while section three is a user's handbook. Section four provides background (over)

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material on the detailed system operation and software assembly. Appendix A contains an explanation of the algorithms used in the software routines and Appendix B flowcharts these routines.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

EVALUATION

As a result of this effort, RADC has acquired the software programs for implementing an operational wideband data link system with an integral ranging capability. By expanding the capabilities of the WCCM ATS system, RADC Contracts F30602-75-C-0120 and F30602-76-C-0101, RADC has established a combined wideband data link/platform locating system. While the system is programmed for first use in support of the Multiple Antenna Surveillance Radar (MASR) demonstration of the Multilateration Radar Surveillance and Strike System (MRS^3) program, it is general enough to serve as a test bed for demonstration/evaluation of other data link or sensor developments.

Stanley M. Yanik

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Project Engineer

SECTION 1

INTRODUCTION

1.1. BACKGROUND

This report documents work performed by Pattern Analysis and Recognition Corporation (PAR) under Contract F30602-77-C-0227 to the Rome Air Development Center (RADC). PAR has improved and updated software which was developed for RADC's Wideband Command and Control Modems (WCCM) Automated Test System under Contract F30602-76-C-0101. The purpose of this effort is to expand the implementation of the WCCM ATS, which is an operational data link system with an integral ranging capability. This system will then be able to support the Multiple Antenna Surveillance Radar (MASR) demonstration of the Multilateration Radar Surveillance and Strike System (MRS^3) program at RADC both as a data link and as a platform locating system.

The remainder of this section summarizes the properties of the WCCM equipment and the accompanying software. Section 2 gives a complete functional description of the WCCM ATS and the data flow into and out of the system. The use of the software is fully described in Section 3. The background needed to understand the detailed operation of the system and how it may be modified is given in Section 4. The algorithms implemented in the software are presented in Appendix A. The flowcharts showing the overall structure of the software are shown in Appendix B.

1.2. WCCM CHARACTERISTICS

The WCCM ATS consists of the WCCM Experimental Model, which was built by Hughes Aircraft Company, and a GT-44 Graphics Display System whose component parts are listed in Table 1-1. The operation of the WCCM hardware is described in Reference 7, a Hughes study document. The major components of the WCCM equipment and paths indicating the flow of information are identified in Figure 1-1. The following paragraph is a simplified summary of how WCCM measures ranges.

The MGCS transmits a continuous, coded bit pattern which contains "frame marks" and messages (both control and data) addressed to the various WCCM units. The units on AR1 and AR2 search the message for the frame marks in order to establish synchronization; when found, they "lock" on the transmitted signal and transmit (on a different frequency) their own coded message. The MGCS searches for the frame mark on the return signal and when it is "locked," it can then measure round trip propagation time from its transmitted frame mark to the receipt of the corresponding frame mark from AR1 and from AR2. This round trip time (which includes measurable equipment delay times) is the basis of the range measurement.

The primary function of the WCCM ATS when it is operated in conjunction with the MRS^3 Test Bed is that of performing X, Y, Z position location calculations for two airborne platforms (AR1 and AR2) and a moving target (MT) on the ground. This is accomplished by using the range measurements made by the WCCM units on the vehicles being tracked, together with the known geographic

Table 1-1 Data Processing Equipment of the GT-44 Graphics Display System

PDP 11/40 CPU (KD -11A)

LA-30 DEC Writer

28 K Words Core Memory (16 K MR11-U and 12 K Monostore VII/Planar)

Two 1.2 Megaword Disk Drives (RKØ5) and Controller (RK-11)

Disk Bootstrap Loader

Display Processor (VT-11) with 17" CRT Monitor and Lite Pen

Programmable Clock (KW 11-P)

Line Frequency Clock (KW 11-L)

Extended Instruction Set (KE11-E)

Floating Instruction Set (KE11-F)

RT-11/GT Operating Software (Version 3B)

RT-11/Basic Option (Version 2)

RT-11 FORTRAN Option (Version 2)

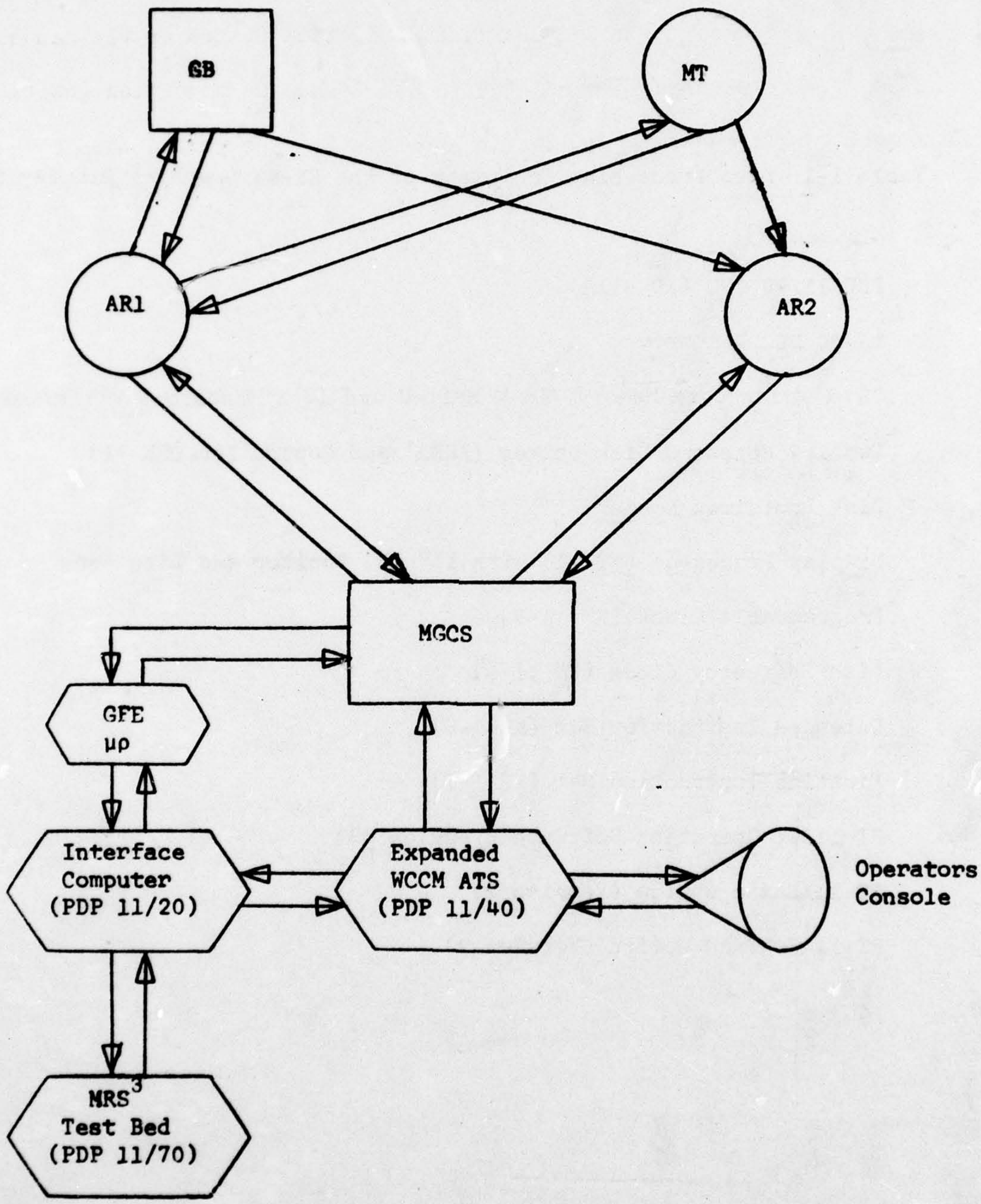

Figure 1-1 Expanded WCCM ATS Environment and Data Flow

locations of the Master Ground Control Station (MGCS) and a secondary Ground Beacon (GB). In addition, altitude data for each vehicle will be made available either from an on-board Inertial Navigation System or via manual entry at the VT-11 Graphics Terminal (GT). The method of computing positions from ranges and altitudes is derived in Appendix A. The position of each vehicle is repeatedly computed in real time and is presented to the ATS operator on the screen of the GT. The position information is also sent to the PDP 11/20 interface computer for relay to other parts of the MRS^3 Test Bed.

WCCM range measurements (actually propagation times which can be converted to ranges) are furnished to the ATS via several paths. The round trip propagation times from the MGCS to both AR1 and AR2 (and return to MGCS) are fed directly from the MGCS to the ATS. Each range is available every thirtieth of a second and the MGCS interrupts the ATS at that rate; every fourth interrupt the ATS inputs the range, time tags it, and enters it into a queue. Other range measurements are made by units in the moving target and airborne platforms and are transmitted down the data links as messages which are consequently relayed to the ATS via the PDP 11/20. These range measurements are time tagged in the air, thus they do not have to be time tagged by the ATS but instead are entered directly into appropriate queues. The measurements made in the air are round trip times from AR1 to GB to AR1 and from AR1 to MT to AR1 and time differences of arrival at AR2 of the signal from MGCS to AR2 and the signal from MGCS to AR1 to GB to AR2 or from MGCS to AR1 to MT to AR2. Associated with all range measurements are certain link and modem status bits.

In addition to its primary function, the Expanded WCCM ATS will also monitor system status, support some automatic and interactive operator control of the system and output periodically computed INS position updates.

The Expanded WCCM ATS is a real-time, interrupt driven system. An important function of the Expanded WCCM software is to ensure that the data flow is truly asynchronous and that all range units remain "locked," and link status is good. The timing structure that is imposed is used to detect when data interrupts are no longer occurring at regular intervals and to initiate the appropriate action for recovery.

The system constantly cycles through an executive loop checking a sequence of flags to determine what action(s) should take place. These flags are set upon receipt of interrupts and data. For example, the receipt of a range measurement and its status causes that data to be entered into a queue and a flag set; upon recognizing the flag, the executive causes the range data to be fed into an appropriate smoothing filter. Similarly, all range measurements are filtered and the system thus has, for each range, a time, a filtered range value at that time, and the time rate of change of that value.

At the frequency with which it is desired to compute the vehicle position(s), an interrupt is generated by an internal clock counter. The executive uses this signal to initiate the position computation which extrapolates the appropriate range filters (and altitude) to a common time and performs a bilateration plus altitude position solution.

Other similarly triggered functions are outputting of the position data and update of the display. Interactive system control by the operator is accomplished by the operator generating interrupts via the display light pen.

The direct support of WCCM as a data link between the MRS^3 Test Bed and the airborne MASR radar is completely transparent to the ATS and is not discussed here or considered part of this effort.

SECTION 2

FUNCTIONAL DESCRIPTION

This section describes the functions performed by the software to operate the WCCM hardware and to analyze the status and range data. As in the previous effort,[5] the programs are divided into two overlays so that the available GT-44 core is used most efficiently. The first performs all the parameter initialization and the second controls the modems and the computations for locating the three vehicles. All system-user communication is accomplished via the terminal keyboard in the first overlay; while in the second, this is accomplished by using the light pen to sense the various buttons displayed on the VT-11 graphics terminal.

2.1. INITIALIZATION AND EXECUTION

The first overlay reads in and stores all the parameters that are used to operate the WCCM modems in the second overlay. First, the user may choose to process only status data or to perform the filtering and position calculations as well. The user next specifies the number of aircraft, which one will function as the relay, and whether or not a moving target is present. Then the type of data, FAKE or REAL, is given. REAL data is input from the DECKIT interface and from the PDP 11/20 computer. FAKE data is read from a simulated data file on disk. If MANUAL mode is selected, the user must start the range filtering and the position calculations by hand after observing that the incoming status is good. Selecting the AUTOMATIC mode causes these two

functions to be initiated without the need for user interaction. The parameters which specify the locations of the master station and the ground beacon, the weather data used for the atmospheric refraction corrections to the ranges, and the electronic signal delays present in the WCCM equipment are read from a disk data file. The values in this file may be changed at will by the user. The display initialization subprograms then format the display buffer and set up the relevant display parameters. The variables which are needed for the second overlay are written from the common area to a disk file.

When the second overlay is brought in, the common data is retrieved from disk and the display is restarted. If REAL data is input, the interrupt service routines for the DECKIT and 11/20 interfaces are initiated. Otherwise the disk reading routine which gets FAKE data is started.

The basic timer is the KW-11P programmable clock which is set to count milliseconds.* This clock is used to set two flags: one for an interval of 10 milliseconds and one for an interval of 1 second. The 10 millisecond flag is used to drive the 10 millisecond counters which include the coast counters and the position counter. The coast counters are set to trip at twice the expected RMU data rate. Thus, if no RMU is forthcoming, these counters will force an entry to be placed on the RMU queue, which in turn will put the Kalman filter in the coast mode. There are also coast counters for the INS set at twice its data rate. The position counter merely sets a flag every 250 milliseconds to signal the position update routine. The 1 second interval

* The KW-11L line clock is also used when in the fake data mode; its operation is described fully in the system programmer's section.

timer is used to drive the display clock, time transfer counters, acknowledge counters, and INS update counters. The display clock is incremented once every second. The time transfer counters and acknowledge counters are preset interval counters which, when runout occurs, force certain checks (see Section 4) to be made. The INS update counters are 15-second interval counters used to signal the INS update routine.

The primary part of the second overlay is the wait loop which continuously checks flags indicating the presence of data to be extracted from the input data (RMU and INS) queues or counter run-outs to start various computations (range filtering, position location and INS updating). When the restart/exit flag is set by light penning the RESTART or EXIT buttons, interrupts are stopped, calculations are completed, any open files are closed and the first overlay is restarted or an exit is made to the RT-11 monitor.

2.2. WCCM INPUTS

The inputs to the WCCM software may be divided into REAL and FAKE data types depending on whether the data originated at the WCCM hardware or was read from a file produced by the scenario generator.

2.2.1. REAL Data

The REAL data is obtained from the WCCM modems. Figure 2-1 gives the format for the DECKIT input interface. RMU #1 gives the round-trip time-of-arrival (TOA) measurement (LSB = 2.03 nanoseconds) between the MGCS and the

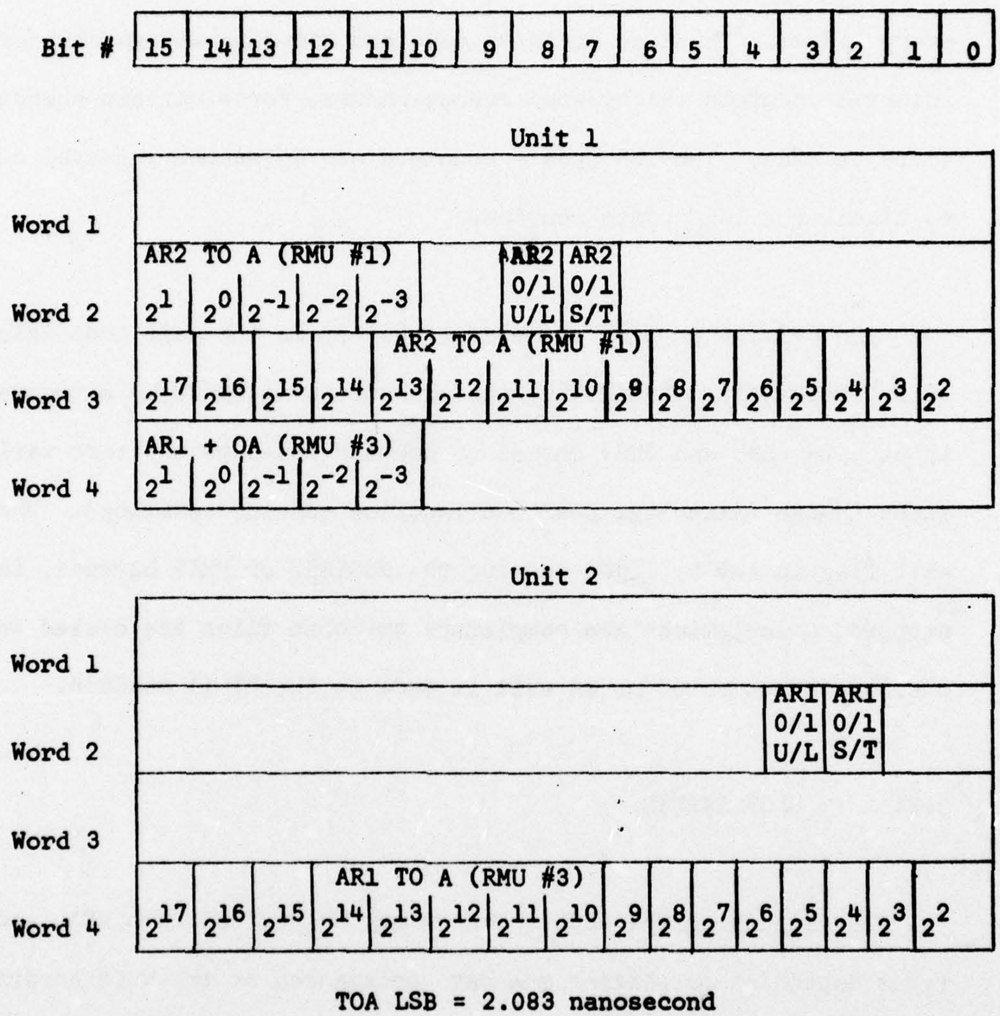

Figure 2-1 DECKIT Input Interface

AR2 aircraft. Similarly, RMU #3 gives the TOA measurement between the MGCS and the AR1 aircraft. The Search/Track bits indicate whether or not the MGCS modem is searching for (0) or in track with (1) the aircraft modem. The Unlock/Locked bits show that the aircraft PN generators are unlocked or locked. These must be locked for the RMU measurements to be valid.

The data transfer from the 11/20 computer is always initiated by sending a word to the 11/40 via a DA-11-B Unibus link. This word contains a message type code in the high order four bits and, if applicable, a word count in the low order portion. This count gives the number of words contained in the message proper which is transferred in the DA-11-B block mode. Four incoming data messages have been defined. These are described briefly below. The detailed formats are given in the accompanying figures.

Type 1: INS Data (Figure 2-2)

This message consists of the first sixteen words of the header of the radar message which the 11/20 receives from the MASR radar ROLM computer. Current plans only call for an INS on AR2, the MASR platform. This message will be received at the radar dwell rate frequency, i.e. every 131 msec, 262 msec, or 524 msec. The WCCM software uses the altitude data in the position computations and the latitude and longitude data in the determination of the position correction.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit #

Platform ID	1
Time	2
(LSB = 1 msec)	3
Latitude	4
(LSB = 360° * 2^{-32})	5
Longitude	6
(LSB = 360° * 2^{-32})	7
North Velocity	8
(LSB = 2^{-19} ft/sec)	9
East Velocity	10
(LSB = 2^{-19} ft/sec)	11
Heading	12
(LSB = 360° * 2^{-32})	13
Roll (LSB = 360° * 2^{-16})	14
Pitch (LSB = 360° * 2^{-16})	15
Altitude (LSB = 1 ft.)	16

Figure 2-2 INS Data (Type 1)

Type 2: Modem Status and RMU Measurement (Figure 2-3)

This message is formatted by the 11/20 from messages received from the GFE microprocessor in the MGCS and which originate at the airborne GFE microprocessors. There are four possible combinations for this message type because there are two airborne platforms, each of which has a link to the ground beacon and the moving target. The frequency of this message is thirty per second (7.5 per combination). The status definitions are given below:

PID	-	Platform Identification 0 or 1 = AR1 or AR2
GID	-	Ground Identification 0 or 1 = MT or GB
CNT	-	RMU Count Value 0 or 1 = not present or present
MT ACK	-	set when airborne microprocessor receives a command for the MT
GB ACK	-	set when airborne microprocessor receives a command for the GB
MT LNK ACK	-	set when airborne microprocessor receives a command acknowledgement from the link with the MT
GB LNK ACK	-	set when airborne microprocessor receives a command acknowledgement from the link with the GB
A-M S/T	-	AR to MT link 0 or 1 = Search or Track
A-G S/T	-	AR to GB link 0 or 1 = Search or Track

	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit #
PID 0/1 1/2	GID 0/1 M/G		CNT 0/1 N/P	MT ACK	GB ACK	MT LNK ACK	GB LNK ACK	A-M 0/1 S/T	A-G 0/1 S/T	M-A 0/1 S/T	G-A 0/1 S/T	GB 0/1 U/L	MT 0/1 U/L	MS-A 0/1 S/T	ROLM	1
TOA Value (LSB = 2.083 nsec)																2
PID 0/1 1/2	GID 0/1 M/G										TOA (HOB)					3
Time																4
(LSB = 1 msec)																5

Figure 2-3 RMU Data (Type 2)

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit #
Time																1
(LSB = 1 msec)																2

Figure 2-4 Time Update (Type 3)

M-A S/T	-	MT to AR link 0 or 1 = Search or Track
G-A S/T	-	GB to AR link 0 or 1 = Search or Track
GB U/L	-	GB Lock Status 0 or 1 = Unlocked or Locked
MT U/L	-	MT Lock Status 0 or 1 = Unlocked or Locked
MS-A S/T	-	MGCS to AR Link 0 or 1 = Search or Track
ROLM	-	ROLM Computer Status (not used by the 11/40)

Type 3: Time of Day Synchronization (Figure 2-4)

This message contains the mission time as kept by the 11/20. Its purpose is to synchronize the clocks for all the computers in the MRS^3 Test Bed. The frequency of this message is presently not determined.

Type 4: This is an indication that the 11/20 is ready to receive data. The format of the output is described in Section 2.3.

2.2.2. FAKE Data

When the expanded WCCM software was written, the hardware to support its operation had not yet been delivered by Hughes Aircraft Company. Therefore, a scenario generator was written to simulate the data inputs so that the system would conform as closely as possible to its operation with REAL data. The scenario program reads in the geographic coordinates of the master station and the ground beacon, the weather data, the speed and coordinates of each vehicle,

the time duration of the scenario, the effective range of the data link, and the error rates for each leg of the link. The position of each vehicle is computed at intervals of 0.1333333 second (7.5 times per second). Two different reference frames are employed, the geographic latitude, longitude, and elevation system and the local topographic X,Y,Z system. Ranges corresponding to the peculiar geometry of WCCM are converted to time-of-arrival values. The path of each vehicle is followed for the duration of the scenario by interpolating linearly between each pair of input coordinates. The turning of corners is simulated by a circular path which has a radius corresponding to a centripetal acceleration of g/3 (g is the acceleration of gravity at the earth's surface). The error rate input is the percentage of transmissions within the data link which fail. The effective range is used as a measure of the length of time a link stays down after it fails.

Each block of data in the scenario file on disk contains data for one second which is organized as shown in Table 2-1. The notation corresponds to that used in the Appendix. The individual item formats are given in Figure 2-5, Figure 2-6, and Figure 2-7. In the last figure, the status bits are defined as follows:

MT ACK	-	Moving Target Acknowledge when set
M-1 S/T	-	MT to AR1 Link 0 or 1 = Search or Track
MT U/L	-	MT Lock Status 0 or 1 = Unlocked or Locked
1-M S/T	-	AR1 to MT Link 0 or 1 = Search or Track

Word Number	Data Item	Repeat Count
1	L_R	
	L_Q	
	L_T	
19	H_R	4
	H_Q	
	H_T	
151	R *	8
255	Ø	2

* The first R item contains data if the second count is even, otherwise it contains zeros

Table 2-1 Scenario Data Record Organization

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit #

Latitude	Word 1
(radians)	Word 2
Longitude	Word 3
(radians)	Word 4
Elevation	Word 5
(meters)	Word 6

Figure 2-5 L Item Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit #

Latitude		Word 1
	(LSB = 360 * 2^{-32} degrees)	Word 2
Longitude		Word 3
	(LSB = 360 * 2^{-32} degrees)	Word 4
North Velocity		Word 5
	(LSB = 2^{-19} ft/sec)	Word 6
East Velocity		Word 7
	(LSB = 2^{-19} ft/sec)	Word 8
Heading		Word 9
	(LSB = 360 * 2^{-32} degrees)	Word 10
Altitude	(LSB = 1 ft)	Word 11

Figure 2-6 H Item Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit #
MT ACK	M-1 0/1 S/T	MT 0/1 U/L	1-M 0/1 S/T	G-2 0/1 S/T	2-S 0/1 S/T	AR2 0/1 U/L	S-2 0/1 S/T	GB ACK	G-1 0/1 S/T	GB 0/1 U/L	1-G 0/1 S/T	M-2 0/1 S/T	1-S 0/1 S/T	AR1 0/1 U/L	S-1 0/1 S/T	Word 1

T_{MR}	Word 2
(LSB = 2.083 nsec)	Word 3
T_{MQ}	Word 4
(LSB = 2.083 nsec)	Word 5
T_{QS}	Word 6
(LSB = 2.083 nsec)	Word 7
T_{QT}	Word 8
(LSB = 2.083 nsec)	Word 9
T_{QSR}	Word 10
(LSB = 2.083 nsec)	Word 11
T_{QTR}	Word 12
(LSB = 2.083 nsec)	Word 13

Figure 2-7 R Item Format

G-2 S/T	-	GB to AR2 Link 0 or 1 = Search or Track
2-S S/T	-	AR2-MGCS Link 0 or 1 = Search or Track
AR2 U/L	-	AR2 Lock Status 0 or 1 = Unlocked or Locked
S-2 S/T	-	MGCS to AR2 Link 0 or 1 = Search or Track
GB ACK	-	Ground Beacon Acknowledge when set
G-1 S/T	-	GB to AR1 Link 0 or 1 = Search or Track
GB U/L	-	GB Lock Status 0 or 1 = Unlocked or Locked
1-G S/T	-	AR1 to GB Link 0 or 1 = Search or Track
M-2 S/T	-	MT to AR2 Link 0 or 1 = Search or Track
1-S S/T	-	AR1 to MGCS Link 0 or 1 = Search or Track
AR1 U/L	-	AR1 Lock Status 0 or 1 = Unlocked or Locked
S-1 S/T	-	MGCS to AR1 Link 0 or 1 = Search or Track

The rate at which the data from each odd and even scenario record is output to the rest of the WCCM routines is shown in Table 2-2.

2.3. WCCM OUTPUTS

The most important output from the WCCM software are the graphics displayed on the VT-11 screen of the GT-44. The current state of the complete

Table 2-2 Scenario Data Output Table

Odd 60^{th} Second	Data Item	Time	Odd 60^{th} Second	Data Item	Time	Odd 60^{th} Second	Data Item	Time	Even 60^{th} Second	Data Item	Time	Even 60^{th} Second	Data Item	Time	Even 60^{th} Second	Data Item	Time
1	T_{MR}	0.13333	21	T_{QT}		41	T_{MR}	0.8000	5	T_{QT}		25	T_{MR}	1.46667	45	T_{QT}	
2	T_{MQ}		22	T_{QSR}		42	T_{MQ}		6	T_{QSR}		26	T_{MQ}		46	T_{QSR}	
3	T_{QS}		23	T_{QTR}		43	T_{QS}		7	T_{QTR}		27	T_{QS}		47	T_{QTR}	
4	h_R	0.13333	24	h_Q		44	h_T		8	h_R	1.2000	28	h_Q		48	None	
5	T_{QT}		25	T_{MR}	0.53333	45	T_{QT}		9	T_{MR}	1.2000	29	T_{QT}		49	T_{MR}	1.86667
6	T_{QSR}		26	T_{MQ}		46	T_{QSR}		10	T_{MQ}		30	T_{QSR}		50	T_{MQ}	
7	T_{QTR}		27	T_{QS}		47	T_{QTR}		11	T_{QS}		31	T_{QTR}		51	T_{QS}	
8	h_Q		28	h_T		48	None		12	h_Q		32	None		52	h_T	
9	T_{MR}	0.26667	29	T_{QT}		49	T_{MR}	0.93333	13	T_{QT}		33	T_{MR}	1.6000	53	T_{QT}	
10	T_{MQ}		30	T_{QSR}		50	T_{MQ}		14	T_{QSR}		34	T_{MQ}		54	T_{QSR}	
11	T_{QS}		31	T_{QTR}		51	T_{QS}		15	T_{QTR}		35	T_{QS}		55	T_{QTR}	
12	h_T		32	None		52	h_R	0.93333	16	None		36	h_T		56	h_R	2.0000
13	T_{QT}		33	T_{MR}	0.66667	53	T_{QT}		17	T_{MR}	1.33333	37	T_{QT}		57	T_{MR}	2.0000
14	T_{QSR}		34	T_{MQ}		54	T_{QSR}		18	T_{MQ}		38	T_{QSR}		58	T_{MQ}	
15	T_{QTR}		35	T_{QS}		55	T_{QTR}		19	T_{QS}		39	T_{QTR}		59	T_{QS}	
16	None		36	h_R	0.66667	56	h_T		20	h_T, h_Q		40	h_R	1.73333	60	h_Q	
17	T_{MR}	0.4000	37	T_{QT}		1	T_{MR}	1.0667	21	T_{QT}		41	T_{MR}	1.73333	61	T_{QT}	
18	T_{MQ}		38	T_{QSR}		2	T_{MQ}		22	T_{QSR}		42	T_{MQ}		62	T_{QSR}	
19	T_{QS}		39	T_{QTR}		3	T_{QS}		23	T_{QTR}		43	T_{QS}		63	T_{QTR}	
20	h_R		40	h_Q		4	None		24	h_R	1.46667	44	h_Q		64	h_T	

WCCM system is shown in tabular and diagrammatic formats so that the user may remain in complete control at all times. A diagram of the screen appears in Figure 2-8. The perimeter is labelled by areas which will be used in the description.

Area 1 contains all the system command light buttons through which the user communicates with the software and controls the hardware. Several commands have subcommands which must be selected by the user. The associated subbuttons appear in the right column of area 1. A list of all the subbuttons is given in Table 2-3. The instructions for their use are detailed in Section 3, the User's Manual. Area 2 is used to inform the user of various error conditions and other relevant information about the system. It also gives the time of day, the name of the current recording file, and the number of disk blocks available for recording. Area 3 presents the vehicle location information in Tabular form. The units of the X,Y,Z coordinates, altitude and range are kilometers. The speed is given as kilometers per hour. The bearing is the direction to the vehicle relative to the origin and measured clockwise from true north. The heading is the direction of the velocity vector and is also measured clockwise from true north. The bearing and the heading both have units of degrees. The values of the ranges as output by the Kalman Filter are given in Area 4. The ranges correspond to the links as follows:

AR1 - MG Range:	MGCS to AR1 to MGCS Link
AR1 - GB Range:	AR1 to GB to AR1 Link (AR1 is relay) or AR2 to GB to AR1 Link (AR2 is relay)
AR2 - MG Range:	MGCS to AR2 to MGCS Link

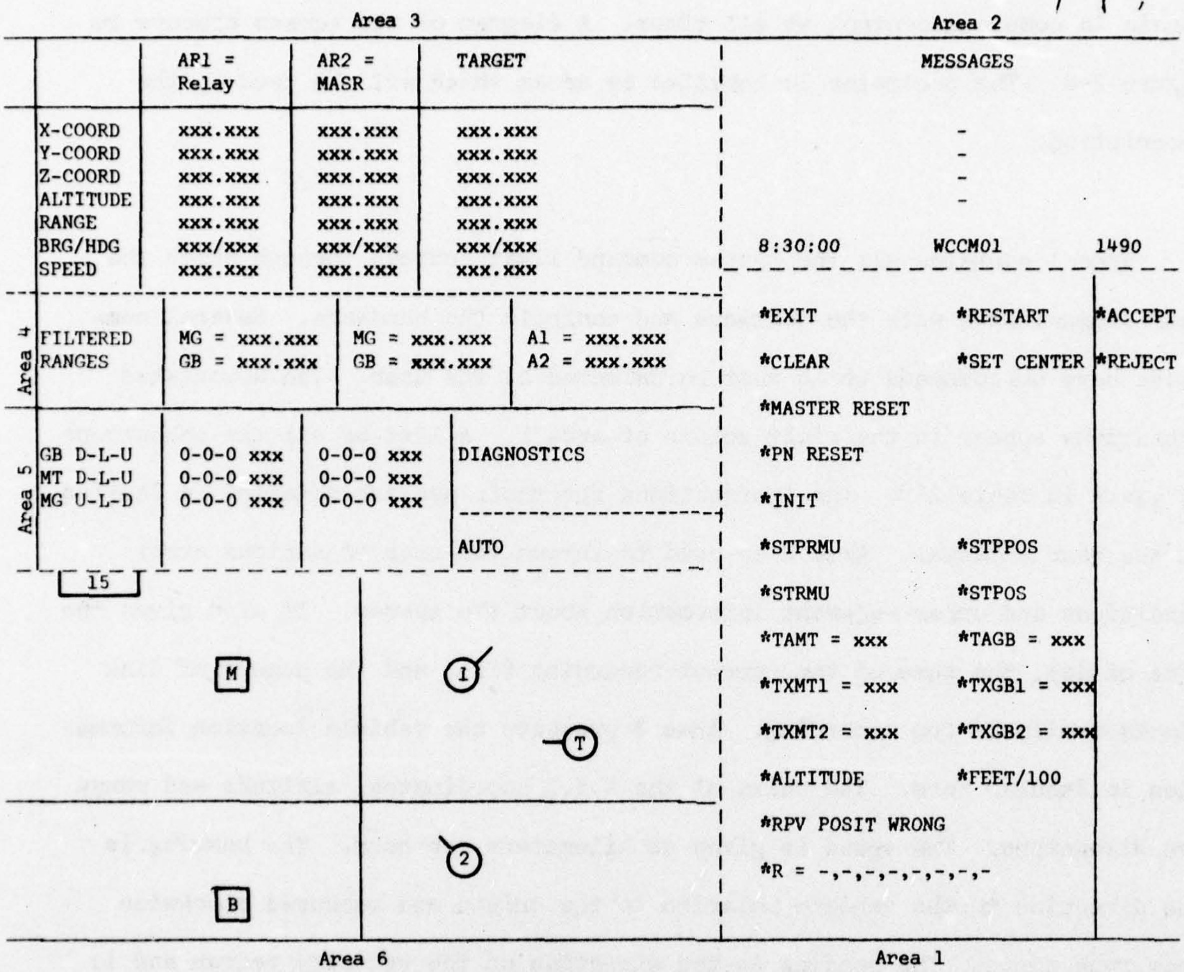

Figure 2-8 WCCM Graphics Display

BUTTON	SUBBUTTON	BUTTON	SUBBUTTON
*SET CENTER	*CENTER		
*INIT	*A1MT *A1GB *A2MT *A2GB	*ALTITUDE	*A1 *A2 *MT *INSAR1 *INSAR2 *INSMT
*STPRMU *STRMU	*A1-MT *A1-GB *A2-MT *A2-GB *A1-MG *A2-MG *ALL *RETURN	*A1 *A2 *MT	*COARSE *FINE 320 (ft) or 975 (meters) 123 0
*STPPOS *STPOS *RPU POSIT WRONG	*A1 *A2 *MT *ALL *RETURN	*FEET/100 *METERS/10	*FEET *METERS
*TAGB *TAMT *TXGB1 *TXGB2 *TXMT1 *TXMT2	*COARSE *FINE 999 123 0	*R = STOP	*RAWR *RAWI *DISP *RANGE *ALTS *POSIT *UPDATE *ON *OFF *RUN *STOP

Table 2-3 Light Buttons and Corresponding Subbuttons

AR2 - GB Range:	AR1 to GB to AR2 Link (AR1 is relay) or AR2 to GB to AR2 Link (AR2 is relay)
Target - A1 Range:	AR1 to MT to AR1 Link (AR1 is relay) or AR2 to MT to AR1 Link (AR2 is relay)
Target - A2 Range:	AR1 to MT to AR2 Link (AR1 is relay) or AR2 to MT to AR2 Link (AR2 is relay)

The status data is shown in Area 6. The D and U parameters refer to the track status of the downlink and the uplink, respectively. The L parameter pertains to the locked status of the link. Each of these values is received 7.5 times per second per RMU. The values displayed are the sums for the preceding second. A threshold level, currently set at 6, is used to indicate whether or not the accompanying RMU data should be filtered or the status indicates the RMU is unreliable and the range data should be coasted by the filter. The method of changing the threshold value is given in Section 4, the System Programmer's Manual. If AR1 is the relay, the D and L values for the GB and MT links to AR2 are always zero. Similarly, the D and L values for the GB and MT links to AR1 are always zero if AR2 is the relay. To the right of Area 5 is reserved space for various diagnostics which are described in the System Programmer's Manual. The mode of operation, Status Only, Automatic or Manual, is also shown in this region. A diagram of station and vehicle locations is displayed in Area 6. The squares show the positions of the MGCS and the GB. The circles shown the positions of the AR1, the AR2 and the MT. The tails on the circles indicate the direction of motion. The cross hairs show the origin of the local topographic coordinate system. The scale at the upper left shows the approximate number of kilometers per inch on the display. The SET CENTER button displays a light pennable cursor which may be moved to any

point in Area 6 which is desired as the center of the display. The diagram is automatically scaled to keep all the symbols within the bounds of the region.

The WCCM commands to the data link are output via the DECKIT Interface. The various bit assignments are shown in Figure 2-9. The Timing Transfer (TX) word must reflect the range difference between each AR vehicle and either the GB or the MT. Noting that the LSB of the TX value is 8.333 sec (or 2.5 km), TDMA acquisition will be accomplished within 6.4 seconds if the estimate is accurate to $\pm$ 1.6 km, 32 seconds for $\pm$ 6.4 km, and 135 seconds for $\pm$ 25.7 km. Acquisition will not be achieved if the range estimate is not accurate to within $\pm$ 25.7 km.

The time assignment (TA) word is used to separate the transmission times of the GB and MT modems which are operating in the time division multiple access (TDMA) mode. If the two TA words are separated by a value of 500, a comfortable guard time is established between the two TDMA signals. The form in which the TX and TA words must be encoded is given in Table 2-4.

There are eight valid addresses used on the Command and Control uplink to AR1 and AR2 from the MGCS. These are:

Address	Message Type
0	AR1 Command
1	AR2 Command
2	AR1 - MT Control
3	AR2 - MT Control
4	AR1 Command
5	AR2 Command
6	AR1 - GB Control
7	AR2 - GB Control

Unit 1

Bit #	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Word 1		TCU INI			Timing Transfer 2^{11}	2^{10}	2^9	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Word 2					Time Assignment 2^{11}	2^{10}	2^9	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Word 3											Address 2^5	2^4	2^3	2^2	2^1	2^0
Word 4																

Unit 2

Bit #	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Word 1																
Word 2																
Word 3												Master Reset				TCU PN Reset
Word 4																

TX LSB = 8.333 μsec (2.5 km)
TA LSB = 33.333 μsec (10.0 km)

Figure 2-9 DECKIT Output Interface

Table 2-4 Time Assignment/Time Transfer Code (complement modulo 10 of the input three-digit number)

DIGIT	4-BIT CODE
1	1001
2	1000
3	0111
4	0110
5	0101
6	0100
7	0011
8	0010
9	0001
0	0000

Example: 235

2	3	5
1000	0111	0101

The procedure used to execute commands is given below:

1. Set invalid address (>7)

2. Insert one or more of the following commands:

   a. Set TX value
   b. Set TA value
   c. Set master reset bit
   d. Set PN reset bit if

3. Set initiate bit

4. Insert desired address for a period greater than 33 msec

5. Reset invalid address

The WCCM software system also outputs navigational update information to the 11/20 which sends the vehicle position data to the 11/70 computer in the MRS^3 Test Bed and sends the INS position corrections to the appropriate vehicle. Current plans call for an INS only in AR2, the MASR platform. The format of this output buffer is shown in Figure 2-10. The details of the position update message are given in Figure 2-11 and the detailed INS update message in Figure 2-12. The negative bit (15) is set each time an individual message is recalculated so that the 11/20 may easily determine if it has already sent that particular message. The complete buffer is sent each time a type 4 indicator is received from the 11/20 and the negative bit for each message is cleared.

Word	Contents
1	AR1 Position and Velocity
17	AR2 Position and Velocity
33	MT Position and Velocity
49	AR1 INS Position Correction
61	AR2 INS Position Correction
73	MT INS Position Correction
84	

Figure 2-10 Navigational Update Buffer Format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit Number
								0					AR1 =1	AR2 =1	MT =1	1
Time																2
(LSB = 1 msec)																3
X Coordinate																4
(Meters)																5
Y Coordinate																6
(Meters)																7
Z Coordinate																8
(Meters)																9
X Velocity																10
(m/sec)																11
Y Velocity																12
(m/sec)																13
Z Velocity																14
(m/sec)																15
Confidence Factor																16

Figure 2-11 Position and Velocity (Type 4)

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit Number
								1					AR1 =1	AR2 =1	MT =1	1
ID				0	1	1	0									2
Time																3
(LSB = 1 msec)																4
North Position								0	0	0	1	1	1	0	0	5
P	Correction (LSB = 1 foot)															6
East Position								0	0	1	1	1	1	0	0	7
P	Correction (LSB = 1 foot)															8
0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	9
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
BALANCR								0	1	1	1	1	1	0	0	11
P	Sum															12

Figure 2-12 Position Correction (Type = 4)

SECTION 3

USER'S MANUAL

This section comprises the User's Manual for the WCCM Software System. The first part gives the detailed instructions for program initialization. The second part details the use of the light button commands. The third section is a special section on the record light button and the final section is a listing and explanation of the error conditions and possible messages.

3.1. PROGRAM INITIALIZATION DIALOGUE

These instructions tell how to start the WCCM software. It is assumed that the WCCM files OVRLY1.SAV, OVRLY2.SAV, and WIKIUP.DAT are all on device DKO. User responses are underlined and must be followed with a carriage return (CR). The program is started by typing R OVRLY1 in response to the system prompt (.). In the following instructions, if any other response besides the two indicated is typed a default value is taken. The default for each question is given below the responses.

Message 1: Status Only (Y or N)?

Response A: Yes - Status Only Mode is chosen

- If this answer is given, skip to message 6

Response B: No - Status mode is disabled

Default: No

Message 2: Number of Planes (1 or 2)?

Response A: 1 Plane - Only one airborne unit is present

Response B: 2 Planes - Two airborne units are present

Default: 2 Planes

Message 3: Relay Plane (1 or 2)?

Response A: Plane 1 - AR1 is the relaying airborne unit

Response B: Plane 2 - AR2 is the relaying airborne unit

Default: Plane 1

Message 4: Moving Target Present (Y or N)?

Response A: Yes - There is a target vehicle in this run

Response B: No - There is no target vehicle in this run

Default: Yes

Message 5: Automatic or Manual Mode (A or M)?

Response A: Automatic - RMUS and positions will start when good status is received

Response B: Manual - RMUS and positions must be started through the use of light button commands

Default: Automatic

Message 6: Input (F or R)?

Response A: REAL - Data input is taken from the DA11B and DECKIT

- If this mode is chosen skip to message 8

Response B: FAKE - Data input is read from a disk file

Default: FAKE

Message 7: File Name?*

Response: A file name of the form DKX:NAME.EXT

X can be 0 or 1

Name can be any RT-11 file name (six characters or under)

EXT can be any three character extension

If none are given DKX: defaults to DK0: and

.EXT defaults to .DAT

Message 8: Parameters OK (Y or N)?

Response A: Yes - Values in WIKIUP.DAT are read for the necessary parameters

Response B: No - The operator has a chance to look at and change the standard parameters in WIKIUP.DAT

Default: No

If the user has answered yes to this question, skip over the following four questions to the explanation of the termination of the first phase.

Parameter Question 1: MGCS: LAT.LON.ELV = (7 Values) OK(Y or N)?

Response A: Yes - User accepts the standard values

Response B: No - User may change the values by typing in seven values separated by commas

Parameter Question 2: GB: LAT.LON.ELV = (7 Values) OK(Y or N)?

Response A: Yes - User accepts the standard values

Response B: No - User may change the values by typing in seven values separated by commas

Following these question the values are printed out in tabular form along with the earth's center X, Y, and Z. This printing is done even if the user answered yes to both of the above questions.

Parameter Question 3: Weather: ELV.TEM.PRE.HUM = (4 Values) OK(Y or N)?

Response A: Yes - User accepts the standard values

Response B: No - User may change the values by typing in four values separated by commas

Parameter Question 4: Delays: MGCS.GB.AR1.AR2.MT = (5 Values) OK(Y or N)?

Response A: Yes - User accepts the standard values

Response B: No - User may enter the delays by typing in five values separated by commas

NOTE: In the above no responses, the user must type in all the numbers for that answer even if he only wishes to change one of the numbers. These numbers must be in floating point format that is: NUMBER.DECIMAL POINT.DECIMAL FRACTION.

After message 8 has been answered with a yes or after parameter question 4 has been completed, the VT-11 screen will light up briefly, go dark for a somewhat longer period, and then light up again. The second overlay is now

executing and all commands are entered through the light buttons on the screen. If the display fails to relight, check to see if a system message ?OVR COR? was received. If it was, this means that the second overlay could not fit in core due to the batch handler being linked to RT-11. To correct this problem reboot the system and type R OVRLY2 to bring up the second overlay. It is not necessary to run OVRLY1 again because the information typed in has been preserved on the disk.

3.2. LIGHT BUTTON COMMANDS

The light pen is used to enter all commands to the WCCM software system. These light button commands can be broken down into six major types. The types and the buttons in the types are listed below:

Operating System Control - RESTART, EXIT
WCCM Interface Control - CLEAR, MASTER RESET, PN RESET, INIT
Internal Software Control - STRMU, STPRMU, STPOS, STPPOS, RV POSIT WRONG
Parameter Entry - TAMT, TAGB, TXMT1, TXMT2, TXGB1, TXGB2, ALTITUDE
Display Control - SET CENTER, FEET/METERS
Recording Control - RECORD

The record button will be detailed in the next section.

3.2.1. Operating System Control

These two buttons allow the operator to perform operations at the operating system level.

EXIT - This button causes the program to halt, the vectors to be restored, any opened files closed, and a return made to the RT-11 operating system.

RESTART - This button does what the exit button does but in addition it recalls the first overlay, thus restarting the program.

NOTE: Due to the nature of the RT-11 VT-11 handler, when the GT on option has been specified before the program was run a clean return will not always take place.

3.2.2. WCCM Interface Control Commands

These commands are used to control the WCCM ground station built by Hughes Aircraft. For the commands to have any effect, the ground station must be in the AUTOMATIC mode.

CLEAR - This command simply clears all the output interface registers.

MASTER RESET - This command toggles the master reset bit in the ground station.

PN RESET - This command toggles the PN reset bit in the ground station.

INIT - This command is used to send Time Assignment (TA) and Time Transfer (TX) information up the link. This command, like most of the others below causes a subbutton list to appear to the right of the main buttons. The subbutton list and the actions taken for each choice is shown below:

A1MT - Send current TAMT and TXMT1 values to the MT and Airborne Unit One

A1GB - Send current TAGB and TXGB1 values to the GB and Airborne Unit One

A2MT - Send current TAMT and TXMT2 values to the MT and Airborne Unit Two

A2GB - Send current TAGB and TXGB2 values to the GB and Airborne Unit Two

3.2.3. Internal Software Control Commands

These commands are used to control the internal workings of the WCCM software system. The actions taken are essentially flag manipulations.

STRMU -

STPRMU - These two buttons are used to START(STRMU) and STOP(STPRMU) the individual RMU filters. As shown in the subbutton list below, these commands

allow multiple RMU filters to be affected in one command entry. The return button is picked to return to the main buttons.

Subbutton List:

- A1MT - the AR1-MT link is affected
- A1GB - The AR1-GB link is affected
- A2MT - The AR2-MT link is affected
- A2GB - The AR2-GB link is affected
- A1MG - The AR1-MGCS link is affected
- A2MG - The AR2-MGCS link is affected
- ALL - All the links are affected
- RETURN - Terminates subbutton entry

When the status only mode has been chosen, the STRMU button is disabled and its use will result in a warning message.

STPOS -

STPPOS - These two buttons work exactly like the RMU buttons above, only the position calculators are affected. The subbutton list is shown below:

- AR1 - AR1 position calculator affected
- AR2 - AR2 position calculator affected
- MT - Target position calculator affected
- ALL - All position calculators affected
- RETURN - Terminates subbutton entry

When the status only mode has been chosen, the STPOS button is disabled and its use will result in a warning message.

NOTE: The following order must be followed when starting the position calculators: Relaying airborne unit, nonrelaying airborne unit, target vehicle. If this order is not followed, the command will be ignored. In the case of the ALL button being chosen, the software will follow this order automatically.

RPV POSIT WRONG - This button is used to indicate to the position calculators that the wrong bilateration solution has been chosen (see functional description). The subbutton list is shown below:

AR1 - AR1 unit is affected
AR2 - AR2 unit is affected
MT - Target unit is affected
ALL - All units are affected
RETURN - Terminates subbutton entry

3.2.4. Parameter Entry Commands

These buttons are used to enter various parameters into the system. The parameters that can be changed by these buttons include the Time Assignment values (TA), the Time Transfer values (TX), and the altitude values.

TAMT -

TAGB - These two buttons are used to change the current time assignment values for the target (TAMT) and the ground beacon (TAGB). The new values are displayed next to the respective buttons. The values are entered through the sliding scale that is displayed in the subbutton region. This scale has two modes of operation, coarse and fine. In the coarse mode, the scale shows the entire range of possible values and entry of any of these values is possible by sliding the light pen up and down the scale. In the fine mode, the range is +/- 10 of the value picked in the coarse range. Exit from the subbutton is done by hitting the ACCEPT button.

TXGB1 -

TXGB2 -

TXMT1 -

TXMT2 - These four buttons allow the user to change the current time transfer value for each of the four TDMA links. The four buttons are necessary because different time transfer values may be needed for airborne unit 1 (TXGB1 and TXMT1) versus those needed for airborne unit 2 (TXGB2 and TXMT2). Entry of the values is done through the same sliding scale used for the time assignments.

NOTE: These values are also updated as a result of an automatic process within the WCCM software. The current value will always be displayed with the button.

Altitude - This button is used in both a parameter entry sense and a control sense. When the button is sensed, a list of subbuttons is shown which allows the user to enter the altitude for the vehicle or enable the ins for that vehicle. The subbutton list and the actions taken are shown below:

AR1 - Sense this for manual entry of the AR1 altitude

AR2 - Sense this for manual entry of the AR2 altitude

MT - Sense this for manual entry of the target altitude

INSAR1 - Sense this to enable the entry of the AR1 altitude from the corresponding INS data

INSAR2 - Sense this to enable the entry of the AR2 altitude from the corresponding INS data

INSMT - Sense this to enable the entry of the target vehicle altitude from the corresponding INS data

When manual entry is selected, the altitude is entered via the same sliding scale used for time assignment and time transfer entry. For more on manual altitude entry, see the section on the feet/meters button.

3.2.5. Display Control Commands

These two buttons are used to control the display itself.

Set Center - This button is used to set the center of the display area in the lower left corner. Sensing the button puts a cursor in this area which can be moved with the light pen. When the center button in the subbutton area

is hit, the display is rescaled and the center is moved to the desired position.

Feet/Meters - This button is used in conjunction with the alitutde button. For manual entry of the altitude, this button allows the entry to be in units of feet/100 or meters/10. The current unit of entry is shown in the button. If the button is changed after an entry, the current value will be converted to the new unit.

3.3. DATA RECORDING FACILITIES

This section describes the data recording capabilities that are controlled by the record light button. Also included in this section is the format of the data file and the use of a small formatting program called "format." The recording feature is activated by sensing the record button. This button brings up a large list of subbuttons which control the recording mode. The first 8 buttons in the sublist are the 8 recording modes available. The next two buttons (on and off) are used to enable or disable the one mode that was just sensed. The last two buttons (run and stop) are used to exit the subbutton list. Run causes recording to start and stop causes the recording to cease.

NOTE: Once the recording feature is in the run state, the operator may sense the record button again to add or subtract various modes. These additions or subtractions are done immediately. This allows changing the recording modes while the recording is actually being done.

3.3.1. Recording Data Modes

The modes of recording can be broken down into three catagories: raw data, intermediate data, and final output data.

Raw Data Modes - There are two raw data modes available: raw range data and raw INS data. Raw range data is selected with the RAWR subbutton and, when selected, is shown in the record button with an R. Raw INS data is selected with the RAWI subbutton and, when selected, is shown in the record button with an I.

Intermediate Data Modes - There are four intermediate data modes available: Kalman filter data, weighted average altitude data, INS correction buffer data, and position calculation buffer data. Kalman filter data is selected with the range subbutton and, when selected, is shown in the record button with a K. Weighted average filter data is selected with the ALTS subbutton and, when selected, is shown in the record button with an A. INS correction buffer data is selected with the ICORR button and, when selected, is shown in the record button with a C. Position calculation data is selected with the POSIT button and, when selected, is shown in the record button with a P.

Final Output Data Modes - There are two modes of final data available: 11/20 update data and display data. 11/20 update data is selected with the UPDAT button and, when selected, is shown in the record button with a U.

Display data is selected with the DISP. subbutton and, when selected, is shown in the record button with a D.

In all cases when the record button is in the run state, any WCCM interface commands that are executed will be recorded.

3.3.2. Recording Data Structures

Each piece of recorded data has an unique code associated with it. This code and the data itself make up a recording file entry. In some cases (some WCCM commands), the code itself is the entry. The present version has a total of 15 different file entries. The entries are detailed in Table 3-1. The entries are ordered by code number.

3.3.3. Data Formatting Program

A short data formatting has been included with the WCCM software to aid in reading the data files created by the WCCM software system. The file is stored under the name FORMAT.SAV and may be run by typing R FORMAT if on the system disk or run DK1:FORMAT if on the DK1 disk. The program asks two questions before it starts interpreting the file. The first question asks the user to input a number for the output device. To use the line printer, type a 6 in response to this question. For terminal output, type a 7. The second question asks for the file name. The file name is given in standard RT-11 format (e.g., DK1:WCCM00.DAT). The extension will default to .DAT if it is

Code	Entry	Length	Word	Format	Description
1	Header	37	1	INT*2	Record Code = 1
			2	INT*4	Millisecond Clock
			4	INT*2	Hours
			5	INT*2	Minutes
			6	INT*2	Seconds
			7	INT*2	Day
			8	INT*2	Month
			9	INT*2	Year
			10	OCT*6	Relay Flag
			11	OCT*6	Planes Flag
			12	OCT*6	Target Flag
			13	OCT*6	Data Type Flag
			14	OCT*6	Mode Flag
			15	OCT*6	Feet/Meters Flag
			16	RAD50	Scenario File Name
			20	REAL*4	X,Y,Z MGCS Coordinates
			26	REAL*4	X,Y,Z GB Coordinates
			32	INT*2	Time Transfer:AR1-MT
			33	INT*2	Time Transfer:AR1-GB
			34	INT*2	Time Transfer:AR2-MT
			35	INT*2	Time Transfer:AR2-GB
			36	INT*2	Time Assignment:MT
			37	INT*2	Time Assignment:GB
2	Raw Range Data	6	1	INT*2	Record Code = 2
			2	OCT*6	Status and ID
			3	INT*4	RMU Value (Ignore Bits 15-7)
			5	INT*4	Time
3	Raw INS Data	17	1	INT*2	Record Code = 3
			2	OCT*6	ID
			3	INT*4	Time
			5	INT*4	Latitude
			7	INT*4	Longitude
			9	INT*4	North Velocity
			11	INT*4	East Velocity
			13	INT*4	Heading
			15	INT*2	Roll
			16	INT*2	Pitch
			17	INT*2	Altitude

Table 3-1 Recording File Data Entry Formats

Code	Entry	Length	Word	Format	Description
4	Display Data	136	1	INT*2	Record Code = 4
			2	REAL*4	AR1 X Coordinate
			4	REAL*4	AR1 Y Coordinate
			6	REAL*4	AR2 Z Coordinate
			8	REAL*4	AR1 Altitude
			10	REAL*4	Range
			12	INT*2	Bearing
			13	INT*2	Heading
			14	REAL*4	Speed
			16-29	Same as above for AR2	
			30-43	Same as above for MT	
			44	INT*2	AR1-MT Plane Acknowledge
			45	INT*2	AR1-GB Plane Acknowledge
			46	INT*2	AR1 MT Link Acknowledge
			47	INT*2	AR1 GB Link Acknowledge
			48	INT*2	AR1-MT Track Count
			49	INT*2	AR1-GB Track Count
			50	INT*2	MT-AR1 Track Count
			51	INT*2	GB-AR1 Track Count
			52	INT*2	AR1 GB Lock Status
			53	INT*2	AR1 MT Lock Status
			54	INT*2	MGCS-AR1 Track Count
			55	INT*2	AR1 ROLM Status Count
			56	INT*2	AR1 Lock Status
			57	INT*2	AR1-MGCS Track Count
			58-71	Same as above for AR2	
			72	INT*2	AR1-GB Messages Received Counter
			73	INT*2	AR1-MT
			74	INT*2	AR2-GB
			75	INT*2	AR2-MT
			76	INT*2	AR1-MGCS
			77	INT*2	AR2-MGCS
			78	INT*2	AR1-MT TT Second Counter
			79	INT*2	AR1-GB TT Second Counter
			80	INT*2	AR2-MT TT Second Counter
			81	INT*2	AR2-GB TT Second Counter
			82	INT*2	MGCS-AR1 TT Second Counter
			83	INT*2	MGCS-AR2 TT Second Counter
			84	REAL*4	AR1-MT Filtered Range
			86	REAL*4	AR1-GB Filtered Range
			88	REAL*4	AR2-MT Filtered Range
			90	REAL*4	AR2-GB Filtered Range
			92	REAL*4	MGCS-AR1 Filtered Range
			94	REAL*4	MGCS-AR2 Filtered Range
			96	REAL*4	AR1 Altitude
			98	REAL*4	AR2 Altitude
			100	REAL*4	MT Altitude
			102	REAL*4	AR1-MT Range Rate
			104	REAL*4	AR1-GB Range Rate

Table 3-1 Recording File Data Entry Formats (Continued)

Code	Entry	Length	Word	Format	Description
			106	REAL*4	AR2-MT Range Rate
			108	REAL*4	AR2-GB Range Rate
			110	REAL*4	MGCS-AR1 Range Rate
			112	REAL*4	MGCS-AR2 Range Rate
			114	REAL*4	AR1 Altitude Rate
			116	REAL*4	AR2 Altitude Rate
			118	REAL*4	MT Altitude Rate
			120	REAL*4	AR1-MT Range Time
			122	REAL*4	AR1-GB Range Time
			124	REAL*4	AR2-MT Range Time
			126	REAL*4	AR2-GB Range Time
			128	REAL*4	MGCS-AR1 Range Time
			130	REAL*4	MGCS-AR2 Range Time
			132	REAL*4	AR1 Altitude Time
			134	REAL*4	AR2 Altitude Time
			136	REAL*4	MT Altitude Time
5	Kalman Filter Data	10	1	INT*2	Record Code = 5
			2	INT*2	ID
			3	INT*4	Raw Range
			5	REAL*4	Filtered Range
			7	REAL*4	Range Rate
			9	REAL*4	Range Time
6	Altitude Filter Data	10	1	INT*2	Record Code = 6
			2	INT*2	ID
			3	INT*4	Raw Altitude
			5	REAL*4	Filtered Altitude
			7	REAL*4	Altitude Rate
			9	REAL*4	Altitude Time
7	Position Calculation Data	49	1	INT*2	Record Code = 7
			2	INT*2	ID
			3	INT*4	Time
			5	REAL*4	AR1 X Value
			7	REAL*4	AR1 Y Value
			9	REAL*4	AR1 Z Value
			11	REAL*4	AR1 X-Dot Value
			13	REAL*4	AR1 Y-Dot Value
			15	REAL*4	AR1 Z-Dot Value
			17	INT*2	Confidence Factor
			18	INT*2	ID
			19	INT*4	Time
			21-32	Same as 5-16 above for AR2	
			33	INT*2	Confidence Factor
			34	INT*2	ID
			35	INT*4	Time
			37-48	Same as 5-16 above for MT	
			49	INT*2	Confidence Factor

Table 3-1 Recording File Data Entry Formats (Continued)

Code	Entry	Length	Word	Format	Description
8	INS Correction Data	36	1	INT*2	Record Code = 8
			2	OCT*6	AR1 ID
			3	OCT*6	INS ID
			4	INT*4	AR1 Time
			6	INT*4	AR1 Delta North
			8	INT*4	AR1 Delta East
			10	INT*4	AR1 Balancr
			12	INT*4	AR1 Checksum
			14	OCT*6	AR2 ID
			15	OCT*6	INS ID
			16	INT*4	AR2 Time
			18	INT*4	AR2 Delta North
			20	INT*4	AR2 Delta East
			22	INT*4	AR2 Balancr
			24	INT*4	AR2 Checksum
			26	OCT*6	MT ID
			27	OCT*6	INS ID
			28	INT*4	MT Time
			30	INT*4	MT Delta North
			32	INT*4	MT Delta East
			34	INT*4	MT Balancr
			36	INT*4	MT Checksum
9	11/20 Update Data	85	1	INT*2	Record Code = 9
			2-49	Same as position calculation data	
			50-85	Same as INS correction data	
20	Master Reset	1	1	INT*2	Record Code = 20
21	Clear	1	1	INT*2	Record Code = 21
22	PN Reset	1	1	INT*2	Record Code = 22
23	INIT A1MT	7	1	INT*2	Record Code = 23
			2	OCT*6	TAMT Value
			3	OCT*6	TAGB Value
			4	OCT*6	TXMT1 Value
			5	OCT*6	TXGB1 Value
			6	OCT*6	TXMT2 Value
			7	OCT*6	TXGB2 Value
24	INIT A1GB	7	1	INT*2	Record Code = 24
			2-7	Same as for INIT A1MT	
25	INIT A2MT	7	1	INT*2	Record Code = 25
			2-7	Same as for INIT A1MT	
26	INIT A2GB	7	1	INT*2	Record Code = 26
			2-7	Same as for INIT A1MT	

Table 3-1 Recording File Data Entry Formats (Continued)

not specified. It is suggested that this program be used only on a line printer as the amount of printing will be quite large.

3.4. SYSTEM MESSAGES

The system messages generated by the WCCM software system can be broken down into two types: informative and fatal. The informative messages are displayed in the upper right corner of the display screen. The fatal messages are displayed on the terminal after the display is removed.

3.4.1. Informative System Messages

1. Message: Acknowledge Received
   Meaning: The link is acknowledging that it has received a message.
   Action: None.

2. Message: No Acknowledge Received
   Meaning: The link has not issued an acknowledge to a message transmission.
   Action: Verify that the radio link still exists.

3. Message: New TT Needed
   Meaning: This message is sent after the system has been successful in sending a new time transfer value. The link acknowledged this message but was unable to lock up using the value received.

Action: Calculate a new time transfer value and enter using the proper TX button and then send the message up the link using the proper INIT sequence.

4. Message: Bad Command For Status Mode

   Meaning: A STRMU or STPOS sequence was requested while in the status only mode.

   Action: Restart display in manual or automatic mode if the action is desired.

5. Message: Record ABORT.?DEV Full? or Record ABORT.NO space

   Meaning: The directory of the recording disk is full or there was no space on the disk.

   Action: Compress the files on the current or mount a new disk if recording is desired.

6. Message: Record ABORT.I/O Error

   Meaning: A hard I/O error was detected while the record routine was trying to write data to the disk.

   Action: Be sure the disk has not been switched off and that the write lock button is off.

7. Message: Record ABORT.?TOO FAST?

   Meaning: A request was made to record data faster than the RK05 is capable of responding.

Action: Turn off at least one of the recording modes and try again.

8. Message: Record End of File

   Meaning: The opened record file space has been used up.

   Action: If desired, open another file.

9. Message: Losing AR Downlink

   Meaning: One of the links between an airborne unit and the MGCS has been down for greater than 135 seconds. To identify the link, look in the ranges section of the display for the zero range value.

   Action: Restore radio contact with the airborne unit.

10. Message: INS Data Link Lost

    Meaning: This message occurs when the INS mode of altitude entry for a vehicle has been enabled but no INS has been received for more than 100 seconds.

    Action: Insure INS unit in the vehicle is still functioning.

3.4.2. Fatal Error Messages

These messages are issued on the terminal after an event has occurred from which recovery is not possible. These error messages should never be seen by the operator of the WCCM system and are included only for the benefit of someone doing system development work.

Message: Trap to Location 4

Meaning: A hardware trap occurred to location 4. This usually occurs because of an odd address being used in an instruction.

Action: A register dump follows and the register 7 value is the address of the instruction following the illegal one. Refer to source listings and make the necessary software changes.

Message: Trap to Location 10

Meaning: This is the same as the above only the trap occurred due to an illegal instruction.

Action: Same as for trap to location 4.

Message: Floating Point Trap

Meaning: An error was detected while a floating point instruction was being executed.

Action: This error usually means that one of the two input values to the floating point function was not what was expected.

Insure that the stack register (KY) has not been overwritten.

Message: INS Queue Overflow

RMU Queue Overflow

Meaning: If one of these two messages appears, the handling of fake data has been slowed down to the point where the program cannot keep up with the input data.

Action: Retry the program. Under the real mode these errors cannot occur.

Message: INVALID INS ID Detected

Meaning: An ID value other than 1, 2, or 4 was detected in the INS data.

Action: Rewrite DQINS code to accept any new ID values.

Message: INVALID 11/20 INTERRUPT SEQUENCE

Meaning: The 11/20 data link protocal has not been followed.

Action: This problem may occur occasionally when starting up the link. It is suggested that the 11/20 be started first.

Message: INVALID 11/20 MESSAGE TYPE

Meaning: An illegal message type was found on the 11/20 data link.

Action: Insure proper 11/20 operation.

Message: Read Error on Common File

Meaning: A hard error has occurred during a read of the COMMON.DAT file.

Action: Retry and ensure proper disk operation.

SECTION 4

SYSTEM PROGRAMMER'S MANUAL

This section contains background information necessary for any person interested in making changes to the WCCM software system. The first sections give a description of the software modules as they now stand and the later section gives instructions for modification to the modules.

4.1. OVERALL STRUCTURE

The entire WCCM software system is too large to fit into the 24K partition available under RT-11 running in a 28K PDP-11. To overcome this limitation the software was broken down into two overlays. The first overlay does program initialization, builds the frame, titles and buttons in the display buffer, and writes this buffer along with several common areas on a disk. This overlay then chains to the second overlay which is the execution phase of the software. The modules necessary for each overlay are shown below:

Overlay #1 - CMMN, OVRLY1, WINDUP, DSPCOM, WDP1, WDP2, WDP3, WDP4, WDP5, WDP7, WDP8, WDP9, WDP15, WDP16, SYSLIB, VTLIB, FORLIB.

Overlay #2 - CMMN, OVRLY2 DA11B, DECKIT, PCLK, LCLK, DQRMU, DQINS, DQCOM, COMMND, CRECRD, POSIT, KALFIL, WAVFIL, DELTIM, SOLUTN, ROTATE, RNGERR, LLHXYZ, INSUPD, INSCOR, DSPCOM,

WDP1, WDP2, WDP3, WDP5, WDP6, WDP7, WDP10, WDP11, WDP12, WDP14, WDP15, WDP16, SYSLIB, VTLIB, FORLIB.

In the above listing there are many files of the form WPDXX. These files make up the VT-11 handler for the WCCM system. They were developed for the first WCCM effort undertaken by PAR Corporation and are detailed in Reference 5 as well as in the listings. In addition some of the other modules are either not documented here or are given only a cursory explanation. In any event the listings should always be consulted for any further explanation that is desired.

4.2. FIRST OVERLAY

The first overlay consists of the two modules OVRLY1 and WINDUP. Please refer to Chart #1 in Appendix B while reading the descriptions of the modules.

OVRLY1 - This module, written in MACRO-11, is the one responsible for asking all the initialization questions detailed in the user's manual with the exception of "parameters OK(Y or N)?" which is asked by WINDUP. The answers to these questions are used to set certain flags in the common block "FLAGS." OVRLY1 is also responsible for initializing several large blocks of core to zero or to certain preassigned values. This initialization process is also done for the VT buffer through a call to the WDP9 routine. Once initialization is complete the VT buffer and the common blocks are written out to a file called common DAT on device DKO. A chain is then made to the second overlay.

NOTE: Both OVRLY.SAV files as well as WIKIUP.DAT must be present on device DK0 for the software to work properly.

WINDUP - This routine, written in FORTRAN-IV, is called from OVRLY1 and is responsible for the initialization question "parameters OK(Y or N)." If this question is answered yes then the values necessary for setup of the Kalman and weighted average filters is read from the disk file WIKIUP.DAT. A no answer to this question causes WINDUP to ask the user for all the necessary values.

4.3. SECOND OVERLAY

The second overlay consists of some 30 modules, not all of which will be detailed here. All the display routines used in the second overlay were written in MACRO-11. Two of these routines, WDP14 and WDP12 will be discussed here, for documentation on the rest see the listings or the technical report previously mentioned (RADC-TR-76-300). Please refer to charts 2 through 12 in Appendix B while reading this documentation.

OVRLY2 - This routine, written in MACRO-11, is the main routine of the second overlay and contains the event flag test loop "WTLOOP." Upon entry the common file created by overlay 1 is read in. Depending on whether real or fake data is to be used the DA11B link and the DECKIT link are initialized or the scenario file is opened and the line clock started. The main execution loop "WTLOOP" is then entered.

In WTLOOP several event flags in the common block flags are tested. These flags control whether or not a call is made to a corresponding subroutine (i.e. the flag RMUQFL and the routine DQRMU). This loop can also be entered from two other places in the WCCM software where a wait is necessary (LPHIT in WDP3 and VTSTP in WDP1). The loop is exited via an RTS PC to one of these two calling modules or through a test at the end of the loop. This test detects if a restart or exit command has been done by the operator or if a hard error has occured. If the test detects any of these conditions the loop is exited and any used vectors are restored. In the case of restart the program is restarted from overlay 1 or in the case of exit or error the program returns to the monitor with an optional error message.

DQRMU - This routine, written in MACRO-11, is called as a result of the RMUQFL being nonzero. This routine is the interface between the RMU queue and the Kalman filter routine "KALFIL." The routine is broken down into two smaller modules "DQ1120" which handles the 11/20 RMUS and "DQWCCM" which handles the WCCM ground station RMUS. In each of the routines the queue element is examined and an ID number established for the RMU (0, 2, 4, 6, 8, or 10). Each RMU has a current state associated with it and a jump is made to that state. "DQ1120" has 7 states and "DQWCCM" has 5 states. A brief description of the states is given below. For a more detailed description see the flowcharts in Appendix B and the statement comments in the listings.

STATE 0 - This state performs a simple deque of the queue element. This state is used as the base state for the manual mode.

STATE 1 - This state performs a simple deque of the queue element if the link is bad. This state is used as the base state for the automatic mode. If the link is good, the state is changed to 1A.

STATE 1A - This is a transitory state between 1 and 2. It causes a fallback to STATE 1 if the link is bad. The state is changed to 2 if the link is good.

STATE 2 - This is the normal running state for the RMUS. If the link goes bad, the state is changed to STATE 3.

STATE 3 - Checking is done in this state for reestablishing a downed link. If the link has been down a short time, the state is changed back to STATE 2. Otherwise the state is changed to the current base STATE(0 or 1). If the link has been down longer than 135 seconds a new time transfer word may be needed. This value is calculated and sent up the link and the state changed to 4.

STATE 4 - Checking is done in this state to see if a link acknowledge was received for the time transfer message sent up in STATE 3. If no acknowledge is received, the message is retried a specified number of times. If an acknowledge is received before this count is reached, the operator is told, the reacquisition counter is started, and the state

is changed to 5. If no acknowledgment is received, then the operator is told and the state goes to the current base STATE(0 or 1).

STATE 5 - Checking is done in STATE 5 to see if the reacquisition timer has runout. If it has, the operator is informed that a new time transfer word is needed and the state is changed to the base STATE(0 or 1).

DQINS - This routine, written in MACRO-11, is called as a result of the INSQFL flag being nonzero. This routine is the interface between the INS queue and the weighted average filter routine "WAVFIL." This routine's structure is very similar to DQRMU. It has only 5 states and STATE 3 is much simpler. For further documentation see the program listing.

INSUPD -

INSCOR - These two routines are responsible for performing the calculation and formatting of the INS update message needed by the Lincoln Labs INS equipment. "INSUPD" is called as a result of one of the INSCXX flags being nonzero. The flag number is passed through register 0. "INSUPD" calls "INSCOR" to get the correction values. "INSCOR," written in FORTRAN-IV, finds the necessary east and north correction by converting the INS data to the local coordinate system, subtracting from the WCCM generated position and returning this difference in INT*4 format. "INSUPD" then takes this value and converts it to the 23-bit data field required by the Lincoln hardware. This routine also sets parity bits needed in the hardware.

DQCOM - This module, written in MACRO-11 contains several routines that perform various housekeeping duties. They are called under flag control from the main wait loop. "ROLLST" is called as a result of the RLSTFL flag being nonzero. This routine takes the status counts that have been building up for the previous second and transfers them to the display area. It then zeroes out the status count area for the next second. "M10RTN" is called as result of the flag M10FL being nonzero. The routine is responsible for updating all the counters that have a 10 millisecond interval. These counters include the coasting counters and the position calculation counter. "SECRTN" is called when the flag SECFLG is nonzero. This routine is used to update all the counters with a second interval. These include the time transfer counters, the display update counter, the status rollover flag, the time of day clock, and the INS counters.

COMINT(WDP14) - This routine, written in MACRO-11, is called when the LPFLAG is nonzero, which occurs as a result of a light pen hit. This routine, like DSPUPD(WDP12), is one of the display package routines. It is detailed here because of it's close connection with the WCCM software. When the operator hits a light button the interrupt service routine sets the LPFLAG and returns the X and Y value of the hit. This flag then causes the WDP14 routine to be entered. Upon entry the X and Y of the hit are checked against the known button X's and Y's. If a match is not found or if it was an illegal match the routine exits. When a valid match is found a jump is made to that button handler. For detail on what each button handler does, see the listings.

DSPUPD(WDP12) - This routine is called when the DSPUPF flag is nonzero. It, along with WDP14 above, forms the main interface between the WCCM software and the WCCM VT-11 handler. The routine is responsible for updating the display once every second. The update includes all the numeric fields as well as the pictorial region in the lower left of the screen. For further details on how this is performed, refer to the display package listings and to the previous PAR Corporation Final Report (RADC-TR-76-300), the ID table allotment used in this program version is included in Appendix C.

CRECRD - This routine is called once every time through the wait loop. The routine along with "PRECRD" forms the data recording portion of the WCCM software. "CRECRD" does all the housekeeping functions that are necessary. These functions include recording of a header block, buffer management, error checking for the write operation, and recording of any WCCM interface commands. "PRECRD" is called from many points within the WCCM software. This module does the actual recording of selected data. Data recording can be one or more of the following types - raw RMU data, raw INS data, Kalman filter data, weighted average filter data, position calculation data, INS correction data, or 11/20 update data. With the record button on the display the user can enable any of these modes of operation. When "PRECRD" is called it receives a code for what type of recording is desired. The routine checks to see if this type of recording was ever enabled, and if so, does the recording. Further detail of the operation of these two modules can be found in the listings.

DA11B - This routine is one of interrupt service routines (ISR) in the WCCM software package. This module contains entry points for setting up the

ISR, stopping the ISR, and the actual ISR itself. This ISR is for the DA11-B link between the 11/20 central message switcher and the 11/40 WCCM controller. The four types of messages that are transferred between these two computers are - raw RMU data (with status), raw INS data, time update, and navigation updates. Of the four, only the navigation update message is formatted in the 11/40. The 11/20 is master of the link and controls when all messages are transferred. It sends a one word transfer with a type and word length which is used to control the subsequent block transfer with the exception that on navigation updates the 11/40 sends this word. The servicing of the block message consists of formatting the data and putting it on a queue, for the raw INS and RMU messages, and converting the time to time of day for the time update message. For navigation requests from the 11/20 the 11/40 formats the message and initiates the block transfer itself.

For further detail on the structure of the messages see the inputs and outputs sections in Section 2 of this manual. For details on the actual handshaking process see the source listings.

DECKIT - This routine, written in MACRO-11, is another of the interrupt service routines. This module, like the DA11B module above, contains routines for starting the ISR, stopping the ISR, and the actual ISR itself. The purpose of this routine is to handle the interface between the 11/40 central processor and the WCCM ground unit built by Hughes Aircraft. Inputs over this interface consists of two RMUs with status. Outputs over this interface consist of control bits and time transfer and time assignment values. For more information on the actual bits used see the inputs and outputs sections

in Section 2. "DECKIT" itself only services the input side of these transactions. The servicing consists of reading the interface, formatting the data, and putting the data on an RMU queue.

PCLK - This simple routine, written in MACRO-11, keeps the system time using the KW11-P programmable clock. The module contains routines for starting the ISR, stopping the ISR, and the ISR itself. The ISR itself is very short and consists simply of updating the main millisecond counter and setting flags for 10 millisecond intervals and for second intervals.

LCLK - This routine, written in MACRO-11, uses the line clock to fake the data load expected under the real operating conditions. The line clock is a 60 Hz clock meaning an interrupt is generated sixty times a second. It was found that by reading a block of data from a scenario file once every second and extracting data from that block once every sixtieth of a second a load very close to the actual anticipated load could be achieved. To achieve all the syncronizations necessary in this type of operation three state variables were used. These state variables tell which RMU is next, which INS is next, and whether an odd or even second is next. The actual reading of the block is done on the fourth tic for both odd and even seconds.

The program begins on the odd second with both the RMU and INS state variables at one. A pause feature is built in which allows the interrupts to occur for one minute before any action is taken. The structure of the disk blocks and a timing chart for the reads is shown in detail in Section 2. Looking at these charts one can see that the odd "second" is actually 56 tics

long and that the even "second" is actually 64 tics long. At the end of the shorter odd second a double INS read is done and the odd/even state variable is set to even. This is done because the three RMUs that are read in the 57th, 58th, and 59th tick are really in the next disk block. Status bits are read in for each set of RMUs and are tagged to each of the RMUs in that set. The status bits read in from the file are converted to the internal form in the routine "STATBTS."

Aside from the main ISR routines there are two programs in LCLK which serve to open and close the scenario disk file. These are "GETSCN" and "CLOSCN."

KALFIL - This routine, written in MACRO-11, is the Kalman filter used to filter the raw RMU data taken from the RMU queue. It is called from the "DQRMU" routine with a flag indicating one of the following three conditions: initialization, regular call, or coast call. For initialization calls the present RMU is stored and the program exits. For the regular call the following series of events happens:

1. The delta time is calculated using the FORTRAN-IV routine "DELTIM"

2. The Q matrix is updated

3. The predicted state is calculated

4. The error covariance matrix of the predicted state is found

5. The Kalman gain is calculated

6. The estimated range is found

7. The error covariance matrix of the estimated range is calculated

8. Exit

For the coast call the routine finds the delta time, the range is updated, and the error covariance matrix of the estimated range is found.

WAVFIL - This routine, written in MACRO-11, is the weighted average filter used to filter the altitudes and the calculated positions. This filter, like KALFIL, is called with a flag indicating one of three conditions: initialization, regular call, or coast call. For initialization calls the altitude or position is stored and the program exits. For regular calls the delta time is found, the weighted average calculations are performed, and the altitude or position updated. For coast calls the delta time is found and the position or altitude updated. Since this module is used by both "DQINS" and "POSIT," care should be taken when modifying the code that one routine's code is not damaged while modifying the other's.

POSIT -

SOLUTN -

RNGERR -

ROTATE - These four modules, written in FORTRAN-IV, make up the position

calculation routines. The main module, "POSIT," first converts the RMU data from time measurements to range measurements taking into account any equipment delays. From these range values the local coordinate position of each of the three vehicles is found. Before this is done checking is done to ensure that the following order of calculation is followed: relay airborne unit, nonrelaying airborne unit, moving target. This order must be kept or the resultant position calculations are very unpredictable. As an example of this order, the moving target position cannot be calculated until the two airborne positions are known. For further description of the methods used in the position calculation, see Appendix A and the functional description section in Section 2.

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APPENDIX A

ALGORITHM DERIVATIONS

A.1. INTRODUCTION

This Appendix derives the algorithms which are implemented in the Expanded WCCM software to support the MRS^3 Test Bed. In this situation, it will be necessary to find the positions of three vehicles, namely, the MASR aircraft and the relay aircraft, as well as the moving target on the ground.

In the following discussion, the extraction of the range measurement from the time-of-arrival data will be considered first. Then the Kalman filter which is used to process the range values is formulated. Third, the method of accomplishing the position location is given. The weighted average filter which is used to obtain velocity estimates is set forth next. Fifth, the INS (inertial navigation system) correction procedure is explained. Finally, the system errors are briefly analyzed.

A.2. RANGE MEASUREMENTS

Three measurements are needed to determine the position coordinates of a vehicle in any system. The ones which will be used in this case are two (2) range measurements from each of two ground stations and the altitude, h, of the vehicle above mean sea level (MSL). This is the so-called bilateration scenario.

A diagram of the data flow to be used in the MRS^3 Flight Tests is shown in Figure A-1. There will be a Master Ground Control Station (M) located at Building 817 at Griffiss Air Force Base and a Slaved Ground Beacon (S) at some other appropriate site. Two aircraft will be used; one will carry the MASR (R) and the other functions as a relay (Q). Finally, a Moving Target (T) will be employed to provide ground truth during the test of the radar.

Six Range Measurement Units (RMU) will provide Time-of-Arrival (TOA) data to a precision of 2.083 nanoseconds (ns). The TOAs are converted to ranges by using the velocity of light, c = 299792458 meters per second (ms^{-1}). The MGCS contains two RMUs which measure two-way ranges to the two airborne vehicles (AR1 and AR2). The RMUs of AR1 measure two-way ranges from AR1 to the GB and the MT. The AR2 RMUs give one-way ranges from AR1 to GB to AR2 and from AR1 to MT to AR2, relative to the time difference between the arrival of the radio signal at AR2 from the MGCS and at AR1 from the MGCS. This is because the signals at AR2 from the MCGS turn on the AR2 RMUs which keep counting until the "dogleg" signals arrive and turn them off.

The relationship between the TOAs (T) and the corresponding ranges (R) including the internal electronic and propagation delays (D) is

$$T_{MR} = 2R_{MR} + D_M + D_R \quad (1)$$

$$T_{MQ} = 2R_{MQ} + D_M + D_Q \quad (2)$$

$$T_{QS} = 2R_{QS} + D_Q + D_S \quad (3)$$

$$T_{QT} = 2R_{QT} + D_Q + D_T \quad (4)$$

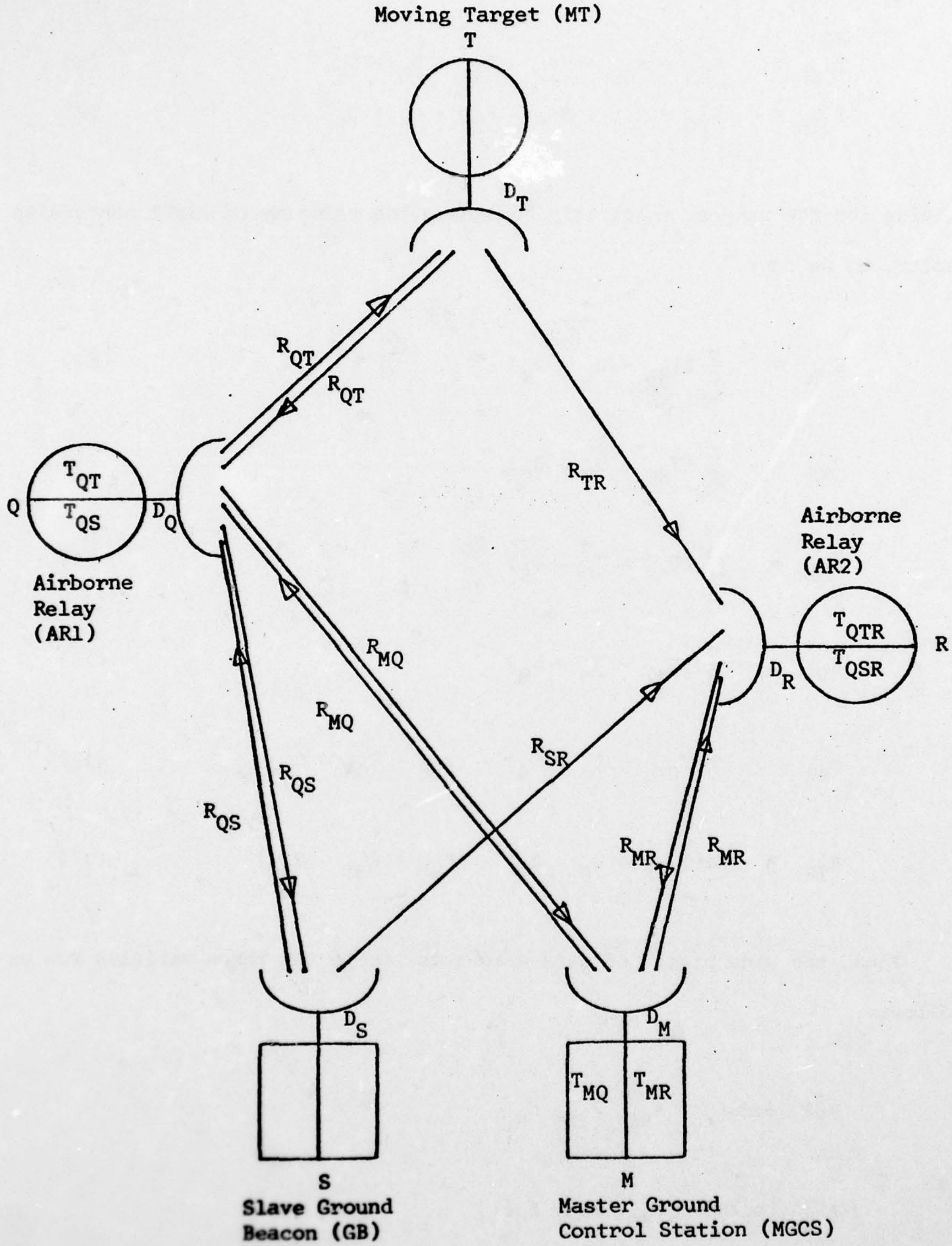

Figure A-1 Ranging Diagram

$$T_{QSR} = R_{MQ} + R_{QS} + R_{SR} - R_{RM} + D_Q + D_S \qquad (5)$$

$$T_{QTR} = R_{MQ} + R_{QT} + R_{TR} - R_{RM} + D_Q + D_T \qquad (6)$$

Solving for the ranges, explicitly including the velocity of light conversion factor, c, we have:

$$R_{MR} = \frac{c}{2}(T_{MR} - D_M - D_R) \qquad (7)$$

$$R_{MQ} = \frac{c}{2}(T_{MQ} - D_M - D_Q) \qquad (8)$$

$$R_{QS} = \frac{c}{2}(T_{QS} - D_Q - D_S) \qquad (9)$$

$$R_{QT} = \frac{c}{2}(T_{QT} - D_Q - D_T) \qquad (10)$$

$$R_{SR} = c(T_{QSR} - D_Q - D_S) - (R_{MQ} + R_{QS} - R_{MR}) \qquad (11)$$

$$R_{TR} = c(T_{QTR} - D_Q - D_T) - (R_{MQ} + R_{QT} - R_{MR}) \qquad (12)$$

Thus, the nine pieces of data needed to locate the three vehicles are as follows:

AR2 (radar) $\rightarrow R_{MR}, R_{SR}, h_R$;

AR1 (relay) $\rightarrow R_{MQ}, R_{QS}, h_Q$;

MT (target) $\rightarrow R_{QT}, R_{TR}, h_T$.

A.3. LINEAR KALMAN FILTER

It is desirable that the algorithms execute as fast as possible, consistent with the requirement of getting sufficiently accurate position estimates. Also, the range measurements described above will be available sequentially, not simultaneously. Therefore, the filtering of the data will be done on the input TOA values and not the position coordinates resulting from the solution. Another advantage of doing this is that a scalar, linear Kalman filter may be used, instead of a vector, nonlinear Kalman filter with its possible convergence problems, long computation times, and large core space requirements.

The variable of interest is the scalar parameter, x, and its rate of change, $\dot{x}$. Its value at any arbitrary time is given by

$$x = (1 \ \tau) \begin{pmatrix} x_i \\ \dot{x}_i \end{pmatrix} \tag{13}$$

where τ is the time difference between the desired time and the time associated with the current values of x_i and $\dot{x}_i$. The Kalman observation equation is

$$\hat{z}_i = g(\underline{x}_i) + V_i \tag{14}$$

where the state vector is

$$\underline{x}_i = \begin{pmatrix} x_i \\ \dot{x}_i \end{pmatrix} \tag{15}$$

and V_i is the noise associated with the measurement process. For the linear observation case, equation (14) may be rewritten

$$\hat{z}_i = \underline{H}\underline{x}_i + V_i \tag{14'}$$

where the observation matrix is

$$\underline{H} = (1\ 0) \tag{16}$$

Equation (14') merely states that the reported value of the scalar parameter of interest, z_i, is the sum of its true value, x_i, and a random error, V_i.

Assume that the filtering started with a specified initial estimate, $\hat{\underline{x}}_o$, and its associated error covariance, $\underline{P}_o$. After the data of observation $\underline{z}_{i-1}$ has been processed, one obtains a best estimate of $\hat{\underline{x}}_{i-1}$ and also an estimate of the error covariance, $\underline{P}_{i-1}$. The equations developed below are then employed to process the next observation, z_i, and to obtain the next estimate of $\hat{\underline{x}}_i$ and its associated covariance of error, $\underline{P}_i$.

The first step is to predict the value of the state vector at the time, i, by using

$$\tilde{\underline{x}}_i = \underline{F}_i\hat{\underline{x}}_{i-1} \tag{17}$$

where the transition matrix is

$$\underline{F}_i = \begin{pmatrix} 1 & \tau_i \\ 0 & 1 \end{pmatrix} \tag{18}$$

The time parameter, τ_i, is the difference between instants i and i-1. There is no noise term in equation (17) because it has been assumed to have a mean value of zero. However, the covariance, $\underline{Q}_i$, must be estimated, although we will assume it depends only upon the $_i$ parameter. The error covariance of the predicted state is

$$\underline{M}_i = \underline{F}_i \, \underline{P}_{i-1} \, F_i^T + \underline{Q}_i \tag{19)*$$

The predicted value of the observation is

$$\tilde{z}_i = \underline{H} \, \underline{\tilde{x}}_i \tag{20}$$

The difference between the actual observation, z_i, and the predicted observation, $\tilde{z}_i$, is a measure of the error in the value of the predicted state vector, $\underline{\tilde{x}}_i$. First computing the Kalman gain

$$\underline{K}_i = \underline{M}_i \, \underline{H}^T (\underline{H} \, \underline{M} \, \underline{H}^T + E)^{-1} \tag{21}$$

where E is the constant error variance of the scalar parameter. The best estimate of the state vector is then

$$\underline{\hat{x}}_i = \underline{\tilde{x}}_i + \underline{K}_i (z_i - \tilde{z}_i) \tag{22}$$

---

* The "T" symbol indicates a transposed matrix.

The covariance of error of this best estimate is

$$\underline{P}_i = (\underline{I} - \underline{K}_i \, \underline{H}) \, \underline{M}_i \, (I - \underline{K}_i \, \underline{H})^T + E\underline{K}_i \, \underline{K}_i^T \tag{23}$$

where $\underline{I}$ is the identity matrix. After obtaining observation, i+1, the Kalman filter is applied recursively by using equations (17)-(23).

The observation covariance is taken to be $E = (1.6 \text{ ns})^2$ for TOA filtering. The system noise covariance matrix will be modelled entirely as accelerations. The input distribution matrix is

$$\underline{W}_i = \underline{A}_i \ddot{x}_i \tag{24}$$

where $\underline{A}_i$ is the acceleration transition matrix

$$\underline{A}_i = \begin{pmatrix} \frac{\tau_i^2}{2} \\ \\ \tau_i \end{pmatrix} \tag{25}$$

and $\ddot{x}_i$ is the acceleration term which we will take to be constant. The maximum acceleration expected for the aircraft is about 1 g or 9.8 m/sec^2, which corresponds to a TOA acceleration of 32.7 nsec/sec^2. For the moving target on the ground, the maximum acceleration is about g/3 or 10.9 nsec/sec^2. The acceleration covariance matrix is

$$\underline{Q}_i = \ddot{x}^2 \underline{A}_i \underline{A}_i^T \tag{26}$$

where $\ddot{x}$ is the appropriate acceleration value.

The method of starting the Kalman filter will now be given. Since a velocity estimate must be obtained, nothing can be done until two measurements are available. The state vector is then

$$\hat{\underline{x}}_1 = \begin{pmatrix} x_1 \\ \\ \dot{x}_1 \end{pmatrix} = \begin{pmatrix} z_1 \\ \\ \dfrac{z_1 - z_0}{\tau_1} \end{pmatrix} \tag{27}$$

The first error covariance matrix is then

$$\underline{P}_1 = \{[\hat{\underline{x}}_1 - \{\hat{\underline{x}}_1\}]\,[\hat{\underline{x}}_1 - \{\hat{\underline{x}}_1\}]^T\} \tag{28}$$

where the curly brackets indicate expectation values. Substituting from above

$$\underline{P}_1 = \left(\begin{array}{c|c} \{(z_1 - \{z_1\})^2\} & \{(z_1 - \{z_1\})\,[\dfrac{(z_1 - \{z_1\}) - (z_0 - \{z_0\})}{\tau_1}]\} \\ \hline \{(z_1 - \{z_1\})\,[\dfrac{(z_1 - \{z_1\}) - (z_0 - \{z_0\})}{\tau_1}]\} & \{[\dfrac{(z_1-\{z_1\})-(z_0-\{z_0\})}{\tau_1}]^2\} \end{array}\right) \tag{29a}$$

$$= \begin{pmatrix} \sigma_1^2 & \dfrac{\sigma_1^2}{1} \\ \\ \dfrac{\sigma_1^2}{\tau_1} & \dfrac{\sigma_1^2 + \sigma_0^2}{\tau_1^2} \end{pmatrix} \tag{29b}$$

We have assumed that the expectation values of the cross term are zero, i.e. the values are not correlated. Both σ_1^2, and σ_0^2 are identified as the observation covariance, E, discussed earlier. Thus,

$$\underline{P}_1 = E \begin{pmatrix} 1 & \frac{1}{\tau_1} \\ \frac{1}{\tau_1} & \frac{2}{\tau_1^2} \end{pmatrix} \tag{29c}$$

and using the initial estimates, $\hat{\underline{x}}_1$, and $\underline{P}_1$, the filtering proceeds using succeeding measurements as described above.

A.4. ATMOSPHERIC RANGE CORRECTIONS

The WCCM equipment measures distances by determining the transit time of a radio signal between two points. The earth's atmosphere has an index of refraction, n, which is slightly greater than unity, e.g., n = 1.000400 is near the maximum observed at sea level. The velocity of light is inversely proportional to n which depends upon the air characteristics, namely pressure, temperature, and the amount of water vapor present. The refractivity parameter, N, which is defined as

$$N = (n-1) \times 10^6 \tag{30}$$

is generally used in the analysis of propogation effects. The expression for the calculation of the refractivity is[1]

$$N = 58.2\,\frac{P}{T} + 2.80 \times 10^{-5}\,\frac{V}{T^2} \qquad (31)$$

where T is the temperature in degrees Kelvin, P is the atmospheric pressure in Torr (mm of Hg), and V is the water vapor pressure in Torr. All measurements must be made at the same elevation and at the same time.

The water vapor pressure may be obtained from the relative humidity, R, by means of the following expressing

$$V = RW \qquad (32)$$

where W, the water vapor pressure for R = 1.00 (100%), is given as a function of absolute temperature (°K = 273 + °C) by

$$\log W = 9.182 - 2328.3/T \qquad (33)$$

Equation (33) was obtained by performing a least-squares fit to tabular data for the vapor pressure of water given in Reference 2.

A range correction algorithm which was developed by IBM[3] is given below:

$$\Delta = a_1 NR + a_2 NRh + a_3 R^3 h + a_4 N + a_5 \qquad (34)$$

where

$$a_1 = 0.96 \times 10^{-6} + 4.003 \times 10^{-11} h_s \tag{34a}$$

$$a_2 = -3.281 \times 10^{-11} - 1.615 \times 10^{-15} h_s \tag{34b}$$

$$a_3 = 1.448 \times 10^{-20} \tag{34c}$$

$$a_4 = -2.286 \times 10^{-2} \tag{34d}$$

$$a_5 = 6.401 - 5.0 \times 10^{-4} h_s \tag{34e}$$

and Δ is the range correction value in meters, R is the measured range in meters, N is the surface refractivity, h_s is elevation above MSL of the surface station in meters, and h is the altitude of the vehicle in meters above MSL. The maximum error of this expression is 3.3 m for $h < 18.3$ km and $R <$ 370.4 km. The typical altitudes encountered in this problem are about 3 km and the maximum ranges are less than 100 km. At these limits, the error is in the neighborhood of 1.1 m. For these ranges, neglecting the a_3 term introduces an additional error of less than 0.05 m. The magnitude of the range correction is 27.2 m at the limits given above. The true range, R_T, is found by using

$$R_T = R_M - \Delta \tag{35}$$

where R_M is the measured range.

Reference 3 points out that the best results are obtained when the water vapor pressure and the atmospheric pressure and temperature measurements are not performed at ground level, but at elevations 200 m to 500 m above the ground. The following expression may be used to scale these measurements for any altitude less than 1 km:

$$N_s = N_M - 7.32 \times 10^{-3}(h_s - h_M)e^{5.577 \times 10^{-3} N_M} \tag{36}$$

where N_s is the station refractivity, h_M is its elevation in meters above MSL, and N_M is the measured refractivity at elevation h_M above MSL.

A.5. POSITION LOCATION

The bilateration problem will be solved in the same manner as was done in the Appendix of Reference 6. The measurements are the range from one station to the vehicle, R_1, the range from a second station to the vehicle, R_2, and the altitude of the vehicle, h. The altitude will be related to the coordinates of the center of the earth which will in effect be the same as a vehicle range, R_3, relative to a third station. Then the three equations in three unknowns which one has available to obtain the solutions are

$$(X - X_1)^2 + (Y - Y_1)^2 + (Z - Z_1)^2 = R_1^2 \tag{37a}$$

$$(X - X_2)^2 + (Y - Y_2)^2 + (Z - Z_2)^2 = R_2^2 \tag{37b}$$

$$(X - X_3)^2 + (Y - Y_3)^2 + (Z - Z_3)^2 = R_3^2 \tag{37c}$$

where the coordinate system is assumed to be an arbitrary local topocentric system with its origin located at a convenient point on the earth's surface.[4] It was shown in the Appendix of Reference 6, that equation (37c) can be written as

$$X^2 + Y^2 + (Z + E)^2 = (E + h)^2 \tag{37d}$$

where E is the distance to the center of the earth from the origin of the local coordinate system. This distance can be approximated[5] by

$$E = q[1 - \frac{e^2}{2} \sin^2 (\lambda - \varepsilon)] \tag{38}$$

where q is the equatorial radius of the earth, e is the eccentricity of the earth ellipsoid, λ is the latitude of the local origin and ε is the surface normal deviation. The approximate value of ε[5] is

$$\varepsilon = \frac{e^2}{2} \sin 2\lambda \tag{39}$$

Equations (38 and 39) are the spherical approximations to the shape of the ellipsoidal earth. These introduce very little error in this case because the ranges which are encountered in this problem are quite small (< 100 km). The solution is considerably simplified if a new coordinate system is defined by a transformation such that

$$X_1, Y_1, Z_1 \rightarrow 0, 0, 0$$

$$X_2,\ Y_2,\ Z_2 \rightarrow x_2,\ 0,\ 0$$

$$X_3,\ Y_3,\ Z_3 \rightarrow x_3,\ y_3,\ 0$$

Then equations (37) become

$$x^2 + y^2 + z^2 = R_1^{\ 2} \qquad (40a)$$

$$(x - x_2)^2 + y^2 + z^2 = R_2^{\ 2} \qquad (40b)$$

$$(x - x_3)^2 + (y - y_3)^2 + z^2 = R_3^{\ 2} \qquad (40c)$$

and solving these we find

$$x = \frac{x_2}{2} + \frac{1}{2x_2}(R_1^{\ 2} - R_2^{\ 2}) \qquad (41a)$$

$$y = \frac{y_3}{2} - \frac{x_3}{y_3}x + \frac{1}{2y_3}(x_3^{\ 2} + R_1^{\ 2} - R_3^{\ 2}) \qquad (41b)$$

$$z = \pm\sqrt{R_1^{\ 2} - (x^2 + y^2)} \qquad (41c)$$

In matrix form, the transformation between the old and the new coordinate systems is

$$\underline{x} = \underline{0}(\underline{X} - \underline{X}_1) \qquad (42)$$

where equations (43), (44), and (45) are, respectively,

$$\underline{x} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \quad \underline{X} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \quad \underline{X}_1 = \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}$$

The reverse transformation is

$$\underline{X} = \underline{0}^T \, \underline{x} + \underline{X}_1 \tag{46}$$

The form of the $\underline{0}$ matrix was given in the Appendix of Reference 6.

A.6. WEIGHTED AVERAGE FILTER

After the position coordinates have been determined, the corresponding velocity components have to be determined. It is also desirable to smooth the position values in order to minimize the effects of numerical truncation, measurement noise, and jumps in the altitudes of the vehicles. It does not appear that the use of the Kalman filter, developed earlier, is justified. The simplest filter for this purpose is the weighted average filter. The velocity estimate is

$$\hat{\dot{x}}_{j+1} = \lambda \hat{\dot{x}}_j + (1 - \lambda) \left(\frac{\tilde{x}_{j+1} - \tilde{x}_j}{\tau_{j+1}} \right) \tag{47}$$

where the caret indicates the smoothed velocity component and the tilde is the component value obtained from the position solution. The weighting parameter, λ, must lie in the range, $-\frac{1}{3} < \lambda < +1$. A value of $\lambda = +\frac{1}{3}$ seemed to give the best results. The smoothed position coordinate is then

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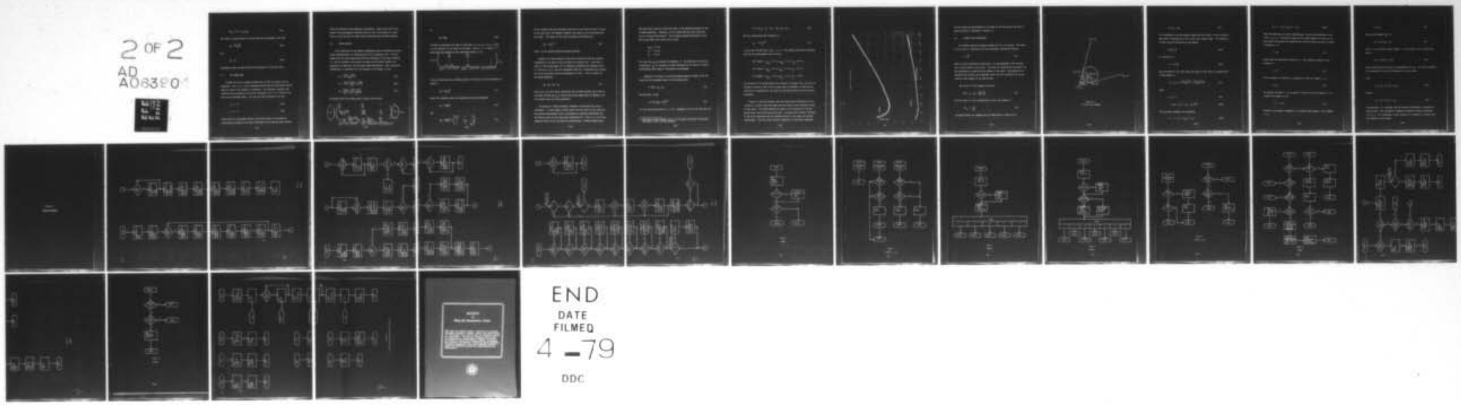

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$$\hat{x}_{j+1} = \hat{x}_j + \tau_{j+1}\,\dot{\hat{x}}_{j+1} \tag{48}$$

The filter is started after two values have been accumulated, such that

$$\dot{\hat{x}}_1 = \frac{\tilde{x}_1 - \tilde{x}_0}{\tau_1} \tag{49a}$$

and

$$\hat{x}_1 = \tilde{x}_1 \tag{49b}$$

Succeeding values are then derived from equations (47) and (48) above.

A.7. INS CORRECTIONS

The MASR INS must be updated periodically so that its accuracy may be maintained. The X, Y, Z local coordinates derived from the WCCM range measurements are used as the standard of comparison. The latitude, longitude, and altitude values reported by the INS are converted to X', Y', Z' values in the WCCM local coordinate system. The east and north corrections are then

$$E = X - X' \tag{50a}$$

$$N = Y - Y' \tag{50b}$$

These values are approximate because true values should be calculated by translating the origin of the local coordinates to the reported WCCM position

before converting the INS geographic coordinates. However, the error introduced by the approximation described above is only a few tenths of a meter which is much less than the other errors associated with the WCCM hardware.

A.8. ERROR ANALYSIS

In the derivation of the analytic expressions used to determine the error values quantitatively, the starting point will be equations (41)... We will assume that the errors associated with the coordinates of the three locations, i.e. the two stations on the earth's surface and the earth's center, are negligible in comparison with the three range measurements. Thus, taking the differentials of equations (41) with respect to the ranges, we find

$$\Delta x = \frac{R_1 \Delta R_1 - R_2 \Delta R_2}{x_2} \tag{51a}$$

$$\Delta y = \frac{-x_3 \Delta x + R_1 \Delta R_1 - R_3 \Delta R_3}{y_3} \tag{51b}$$

$$\Delta z = \frac{R_1 \Delta R_1 - (x\Delta x + y\Delta y)}{[R_1{}^2 - (x^2 + y^2)]^{1/2}} \tag{51c}$$

Collecting terms and writing these in matrix form we have

$$\begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix} = \begin{pmatrix} \frac{R_1}{x_2} & -\frac{R_2}{x_2} & 0 \\ \frac{(x_2 - x_3)R_1}{x_2\, y_3} & \frac{x_3 R_2}{x_2 y_3} & -\frac{R_3}{y_3} \\ \frac{[1 - \frac{x}{x_2} - \frac{y(x_2 - x_3)}{x_2 y_3}]R_1}{[R_1{}^2 - (x^2 + y^2)]^{1/2}} & \frac{(\frac{x}{x_2} - \frac{y x_3}{x_2 y_3})R_2}{[R_1{}^2 - (x^2+y^2)]^{1/2}} & \frac{\frac{yR_3}{y_3}}{[R_1{}^2-(x^2+y^2)]^{1/2}} \end{pmatrix} \begin{pmatrix} \Delta R_1 \\ \Delta R_2 \\ \Delta R_3 \end{pmatrix} \tag{51d}$$

or

$$\underline{\Delta x} = \underline{C}\underline{\Delta R} \qquad (51e)$$

A little consideration will make it clear that x, y, x_2, x_3 << $y_3 \simeq r$ where r is the distance to the center of the earth. Also $R_3 \simeq r + h$ where h << r. Using these approximations, the coefficient matrix, C, is

$$\underline{C} \simeq \underline{C}' = \begin{pmatrix} \frac{R_1}{x_2} & -\frac{R_2}{x_2} & 0 \\ 0 & 0 & -1 \\ \frac{(x_2 - x)R_1}{x_2[R_1^2 - (x^2 + y^2)]^{1/2}} & \frac{xR_2}{x_2[R_1^2 - (x^2+y^2)]^{1/2}} & \frac{y}{[R_1^2-(x^2+y^2)]^{1/2}} \end{pmatrix} \qquad (52)$$

It may be shown that the covariance matrix of the errors in the coordinates is given by

$$\underline{\Sigma}_x = \underline{C}\,\underline{\Sigma}_R\,\underline{C}^T \qquad (53)$$

where (the expected values are indicated by the curly brackets)

$$\underline{\Sigma}_x = \{\underline{\Delta x}\underline{\Delta x}^T\} \qquad (54)$$

and

$$\underline{\Sigma}_R = \{\underline{\Delta R}\underline{\Delta R}^T\} = \begin{pmatrix} \sigma_{R_1}^2 & 0 & 0 \\ 0 & \sigma_{R_2}^2 & 0 \\ 0 & 0 & \sigma_{R_3}^2 \end{pmatrix} \qquad (55)$$

We have assumed that the individual errors have a zero mean and that, as shown by the zero-value, off-diagonal elements, the ranges are not correlated with each other. The errors in the local topocentric coordinates are

$$\underline{\Sigma}_x = O \, \underline{\Sigma}_x \, O^T \qquad (56)$$

where O is the rotation matrix previously derived.

Equation (56) above applies to the errors associated with the position coordinates of the MASR (R) and the Relay (Q) aircraft only. Since the location of the Moving Target (T) is obtained by measuring the distance from R to T and from Q to T, the error associated with the T coordinates must include the errors associated with the coordinates of R and Q. This is simply the following expression

$$\underline{\Sigma}_T = \underline{\Sigma}_R + \underline{\Sigma}_Q + \underline{\Sigma}_X \qquad (57)$$

where $\underline{\Sigma}_R$ is the error matrix associated with the MASR aircraft, $\underline{\Sigma}_Q$ is that of the Relay aircraft and $\underline{\Sigma}_X$ is that of the Moving Target given by equation (56) and obtained under the same assumptions.

The problem of finding numerical estimates of the errors will now be considered. It would appear at first glance that the errors in the range and the altitude measurements could be considered as uniformly distributed over the interval given by the value least significant bit. This is 2.1 ns for the ranges and about 30.5M (100 feet) for the altitudes. Further thought shows

that many other sources of error can occur in the measuring process for each of these quantities. Therefore, we will assume that the error statistics follow a Gaussian distribution. The following standard deviations or root mean square (RMS) error values will be used:

$$\sigma_{TOA} = 1.6 \text{ ns}$$
$$\sigma_{D} = 2.1 \text{ ns}$$
$$\sigma_{h} = 30.5 \text{ m}$$

The value for σ_{TOA} was derived in Reference 7.* The RMS value of the delay calibrations, σ_D, is increased over that estimated for TOA errors to reflect uncertainties which apply to the method of calibration.

Equations (7) through (10) give the range measured in terms of the TOA values and the equipment delays in the following form

$$R = \frac{c}{2}(T - D_1 - D_2) \qquad (58)$$

The RMS value is then

$$\sigma_R = \frac{c}{2}(\sigma_{TOA}^2 + 2\sigma_D^2)^{1/2} \qquad (59)$$

For the values given above, $\sigma_R = 0.5$ m. Equations (11) and (12) have the form

---

* Note that in their equation (5.4.6.), the square root should include the denominator as well as the numerator.

$$R' = c(T_{123} - D_1 - D_2) - (R_1 + R_2 + R_3) \qquad (60)$$

and the corresponding RMS expression is

$$\sigma_{R'} = (5\,\sigma_R^2)^{1/2} \qquad (61)$$

In this case the RMS value is $\sigma_{R'} = 1.1$ m. The standard deviations associated with the nine measurements are as follows:

AR2 (radar) $\rightarrow \sigma_{R_{MR}} = 0.5$, m, $\sigma_{R_{SR}} = 1.1$ m, $\sigma_{h_R} = 30.5$ m

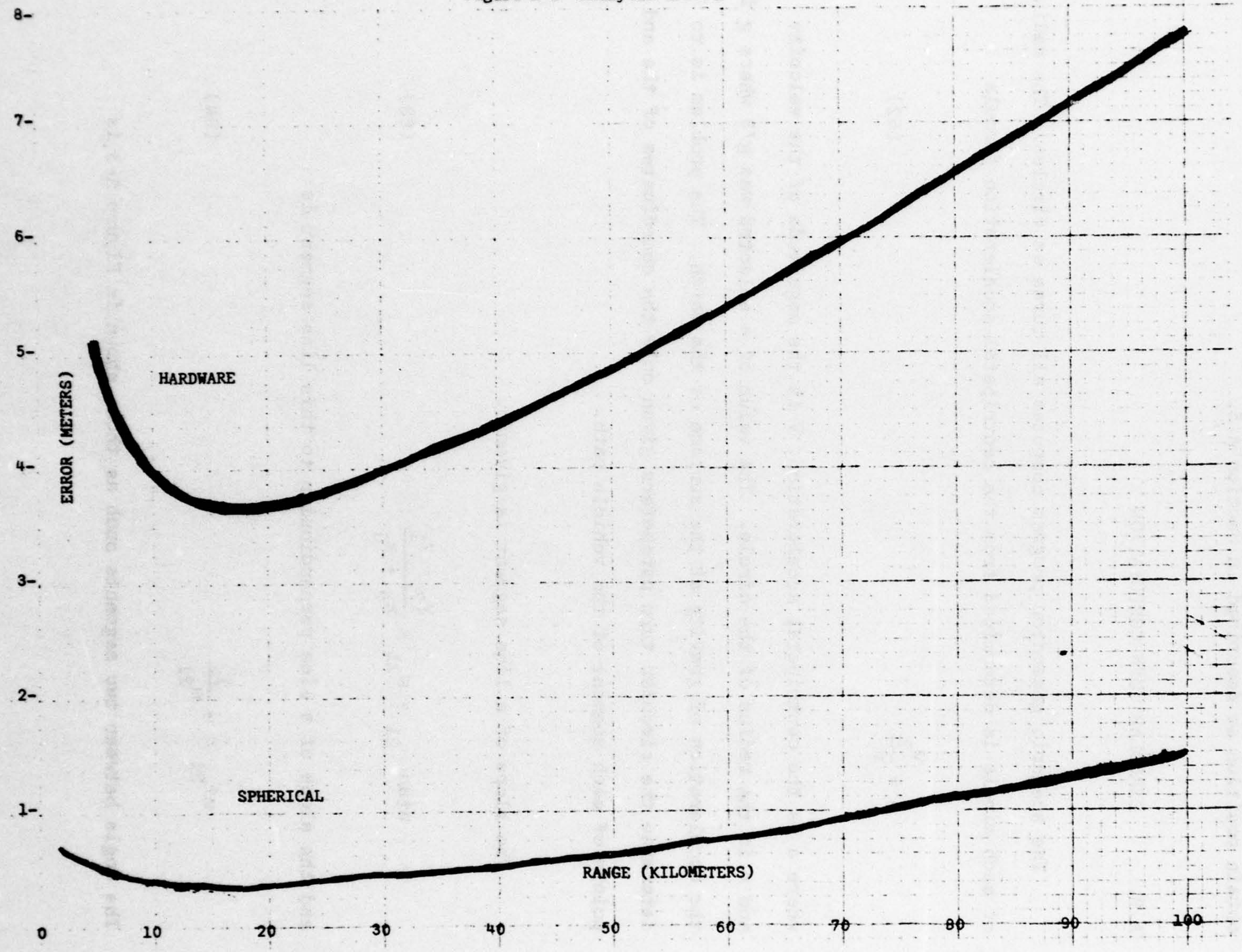
AR1 (relay) $\rightarrow \sigma_{R_{MQ}} = 0.5$ m, $\sigma_{R_{QS}} = 0.5$ m, $\sigma_{h_Q} = 30.5$ m

MT (target) $\rightarrow \sigma_{R_{QT}} = 0.5$ m, $\sigma_{R_{TR}} = 1.1$ m, $\sigma_{h_T} = 3.05$ m

The altitude of the Moving Target will probably be obtained from a map with an accuracy of about 10 feet (3.05 m) rather than an altimeter, so that associated error is substantially less than the altitude obtained from the aircraft altimeters.

Figure A-2 shows the minimum root mean square error associated with the location of a point versus the range from the origin of the coordinate system to that point. The master station was taken to be at Building 817 and the ground beacon was at the Verona Test Site. The upper curve labelled 'Hardware' is the error associated with the estimated errors in the range and altitude measurements. The lower curve labelled 'Spherical' is the error associated

Figure A-2 Analytic Errors



with the spherical approximation to the shape of the earth which was used to obtain position as described in Section A.5.

A.9. CIRCULAR TURN COMPUTATION

The scenario generator program computes all tur s as circles. The radius of each circle is determined from the centripetal acceleration formula

$$a = \frac{V_2}{r} \tag{62}$$

where a is the centripetal acceleration, V is the magnitude of the velocity and r is the radius of the circle. The value of a selected was g/3 where g is the acceleration of gravity at the surface of the earth. The problem is to determine the circular turn parameters given only the coordinates of the end points of each segment of the vehicle path.

The slope of a line segment is given by

$$\alpha\tan_{21} = m_{21} = \frac{y_2 - y_1}{x_2 - x_1} \tag{63}$$

and the slope of a line perpendicular to this line segment is

$$m'_{21} = -\frac{1}{m_{21}} \tag{64}$$

The angle between two segments such as those shown in Figure A-3 is

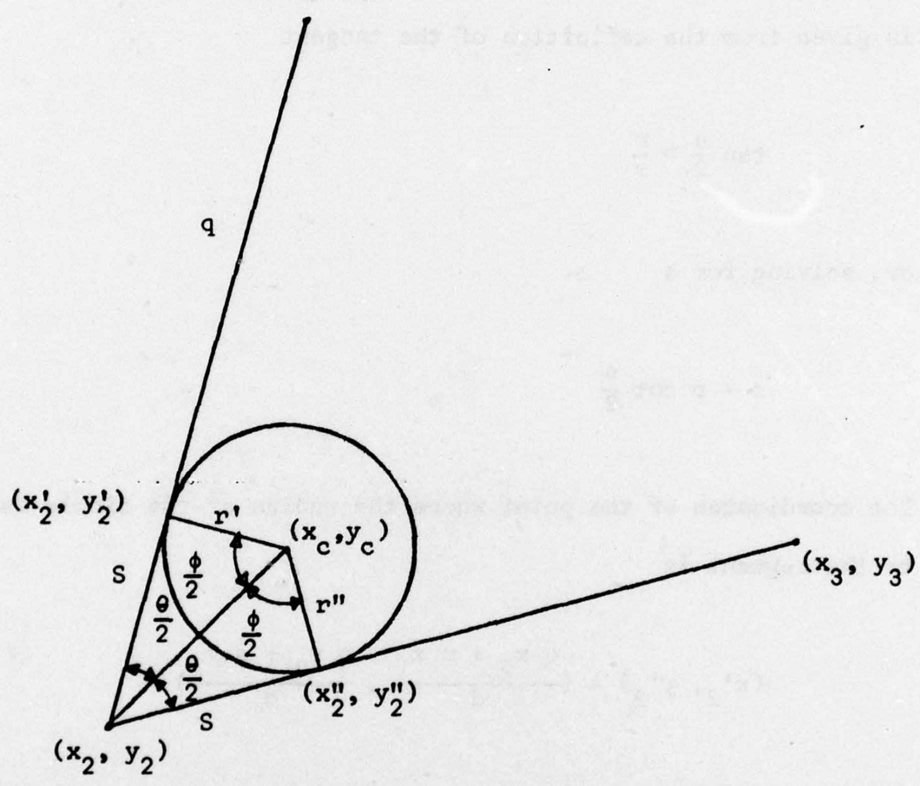


Figure A-3
Circular Turn Diagram

$$\theta = \alpha_{21} - \alpha_{23} \tag{65}$$

It is necessary to use the angles, rather than the slopes, in this problem to keep track of directions, as well as the full angular range. The distance, s, is given from the definition of the tangent

$$\tan \frac{\theta}{2} = \frac{r}{s} \tag{66a}$$

or, solving for s

$$s = r \cot \frac{\theta}{2} \tag{66b}$$

The coordinates of the point where the radius of the circle is perpendicular to the segment is

$$(x'_2, y'_2) = \left(\frac{q\ x_2 + s\ x_1}{d}, \frac{q\ y_2 + s\ y_1}{d}\right) \tag{67}$$

where

$$d = q + s \tag{68}$$

$$= [(x_2 - x_1)^2 + (y_2 - y_1)^2]^{1/2} \tag{68b}$$

The two radial segments, have equations

$$r': \quad y - y'_2 = m'_{21}(x - x'_2) \tag{69a}$$

$$r'': \quad y - y''_2 = m'_{23} (x - x''_2) \tag{69b}$$

These two equations are solved simultaneously to give the coordinates of the circle, (x_c, y_c). The angle between the two radial segments is found in the same manner as described for equations (63) and (65) above, and the arc length subtended by ϕ is

$$\ell = r\phi \tag{70}$$

Assume that the calculation interval is t. The distance traveled in each interval is

$$\rho = Vt \tag{71}$$

Thus the number of intervals, n, necessary to cover the length, ℓ, is

$$n = \frac{\ell}{\rho} \tag{72}$$

The angular increment, ε, to be applied n times so that line segment 1-2 is rotated into segment 2-3 is

$$\varepsilon = (\pi - \theta)/n \tag{73}$$

Similarly, the angular increment, δ, to rotate radial segment r' into segment r'' is

$$\delta = \phi/n \tag{74}$$

The new line segment slope is

$$m_i = \tan(\alpha_{21} + i\varepsilon) \tag{75}$$

where i is the current interval number. In like manner, the new radial segment is

$$m'_i = \tan(\alpha'_{21} + i\delta) \tag{76}$$

where prime indicates the angle is perpendicular to α_{21}. Two linear equations are intersected to give the coordinates of the new point.

line:

$$y_i - y_{i-1} = m_i (x_i - x_{i-1}) \tag{77a}$$

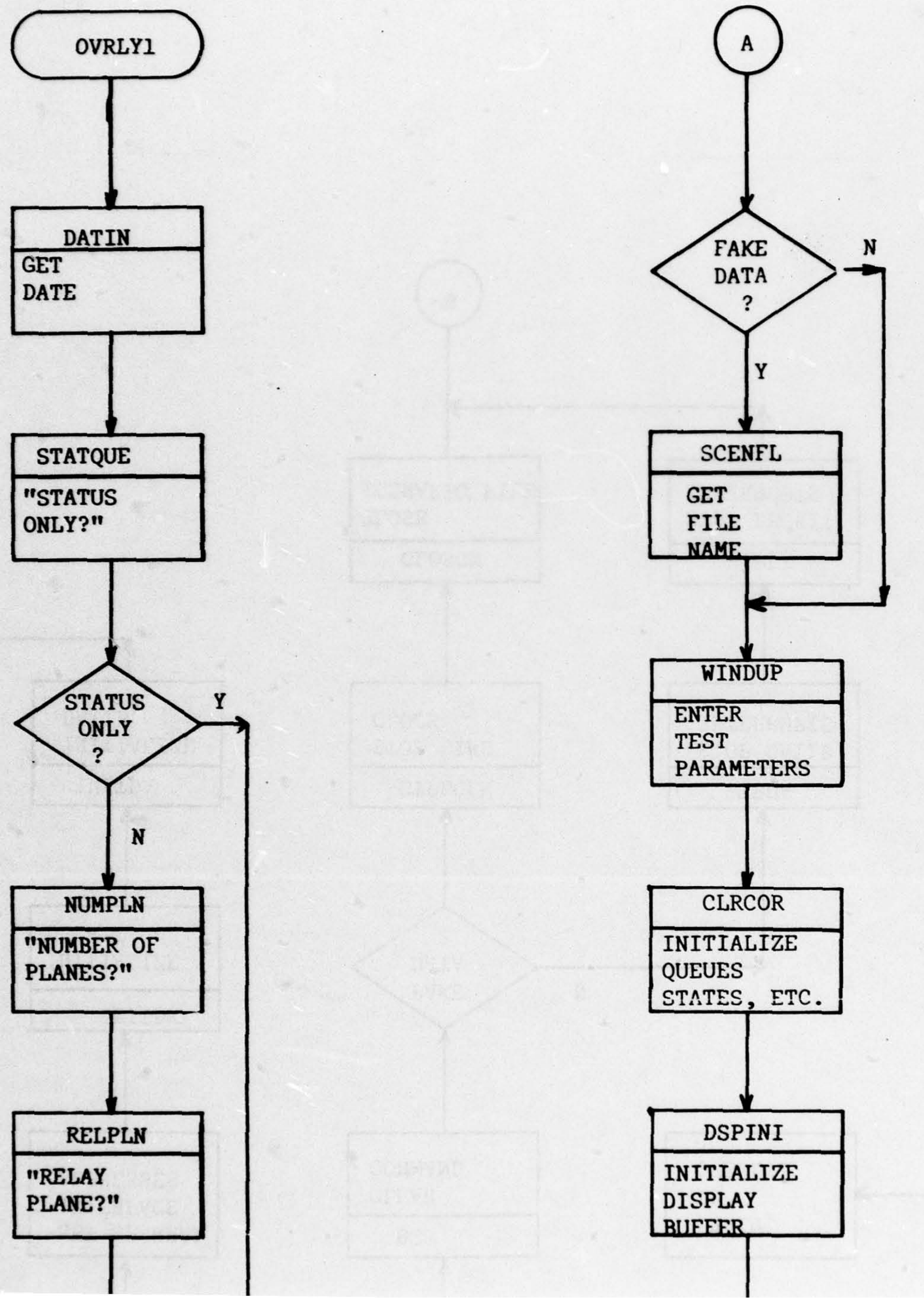
radius:

$$y_i - y_c = m'_i (x_i - x_c) \tag{77b}$$

The subscript, i-1, indicates that the previous coordinates of intersection must be used. This procedure is started by using the initial coordinates, (x'_2, y'_2). The coordinates of each vehicle as it undergoes a circular turn are obtained in this manner.

APPENDIX B

SYSTEM FLOWCHARTS



OVRLY1
DATIN
GET DATE
STATQUE
"STATUS ONLY?"
STATUS ONLY ?
Y
N
NUMPLN
"NUMBER OF PLANES?"
RELPLN
"RELAY PLANE?"
A
FAKE DATA ?
N
Y
SCENFL
GET FILE NAME
WINDUP
ENTER TEST PARAMETERS
CLRCOR
INITIALIZE QUEUES STATES, ETC.
DSPINI
INITIALIZE DISPLAY BUFFER

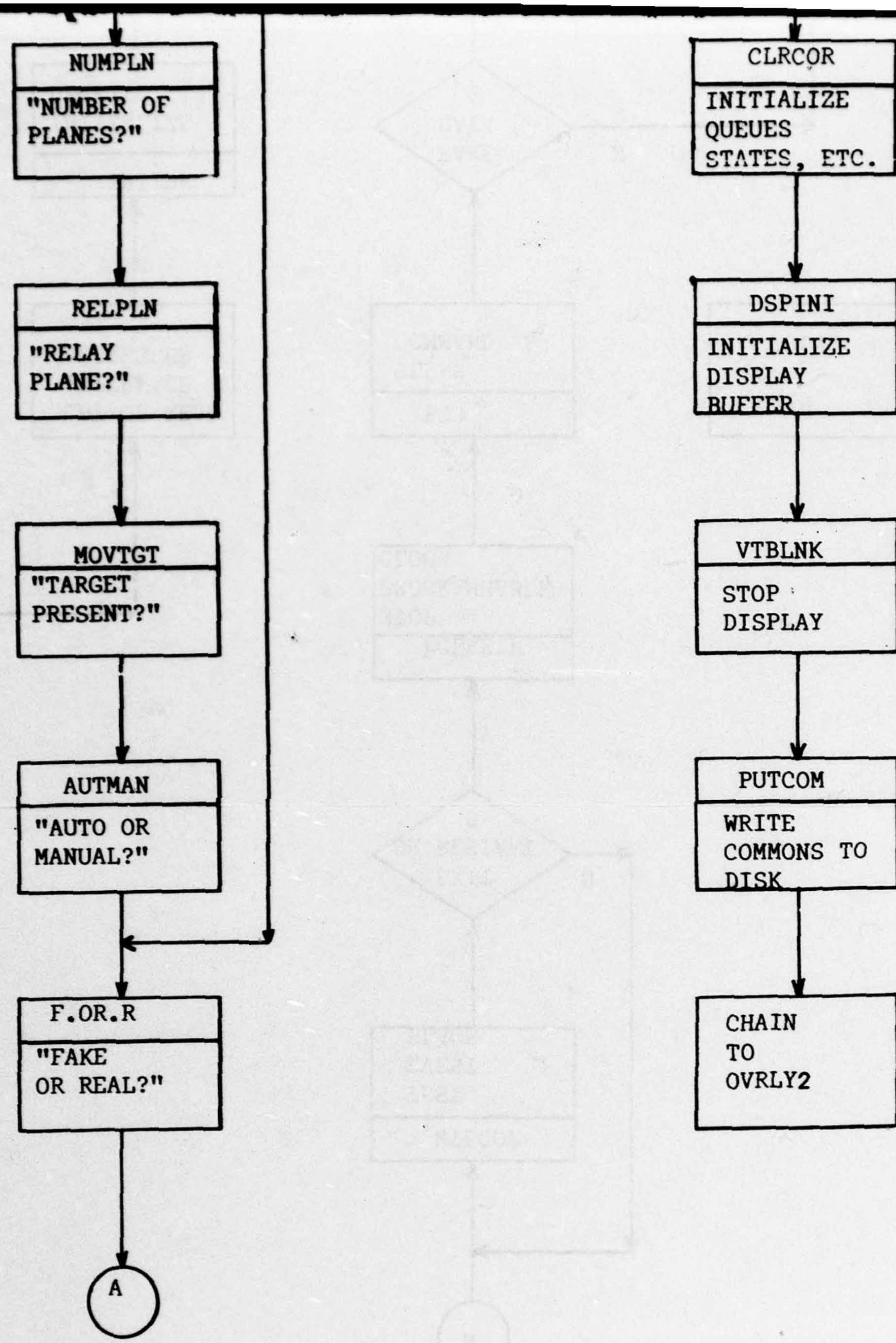
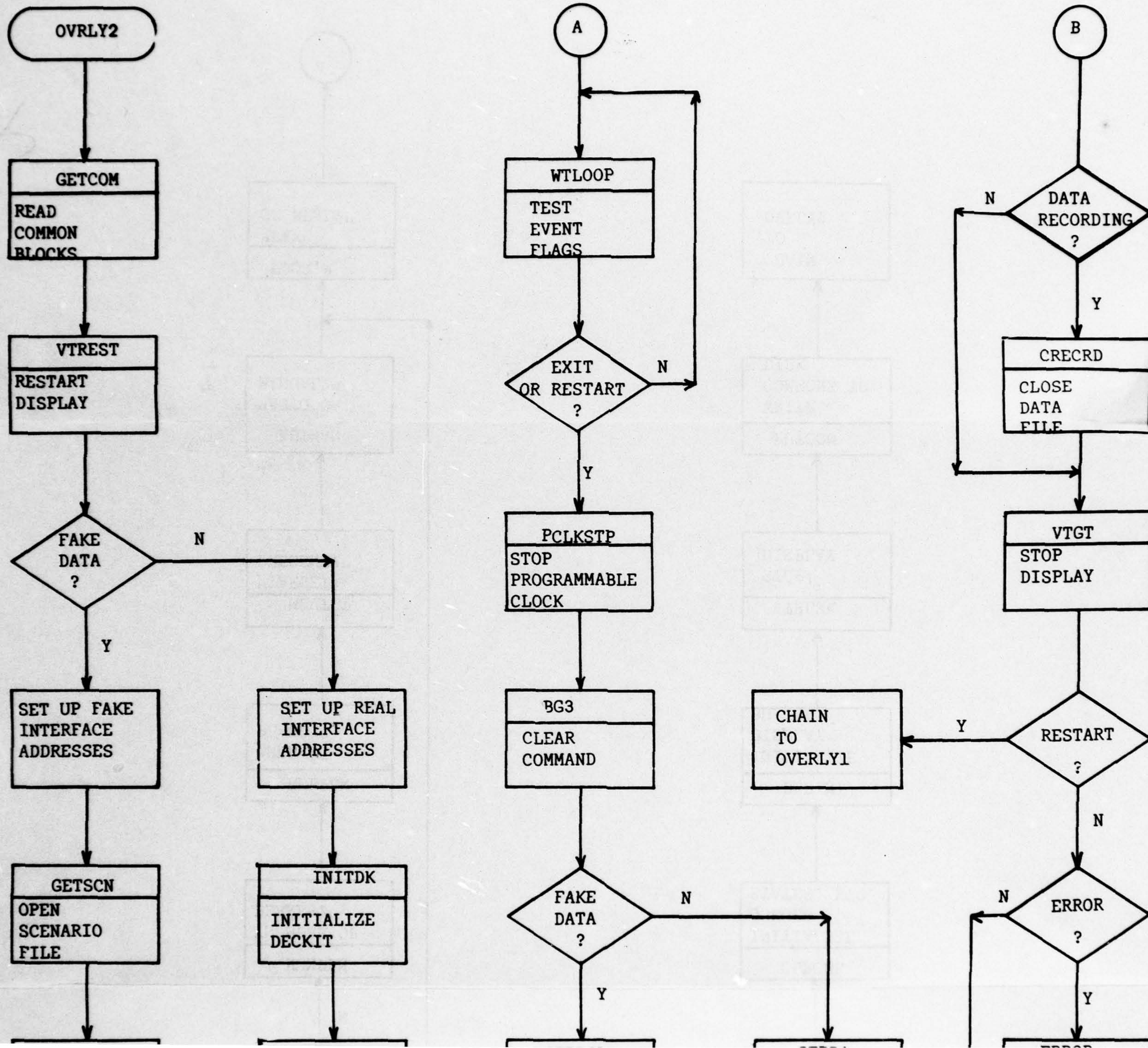


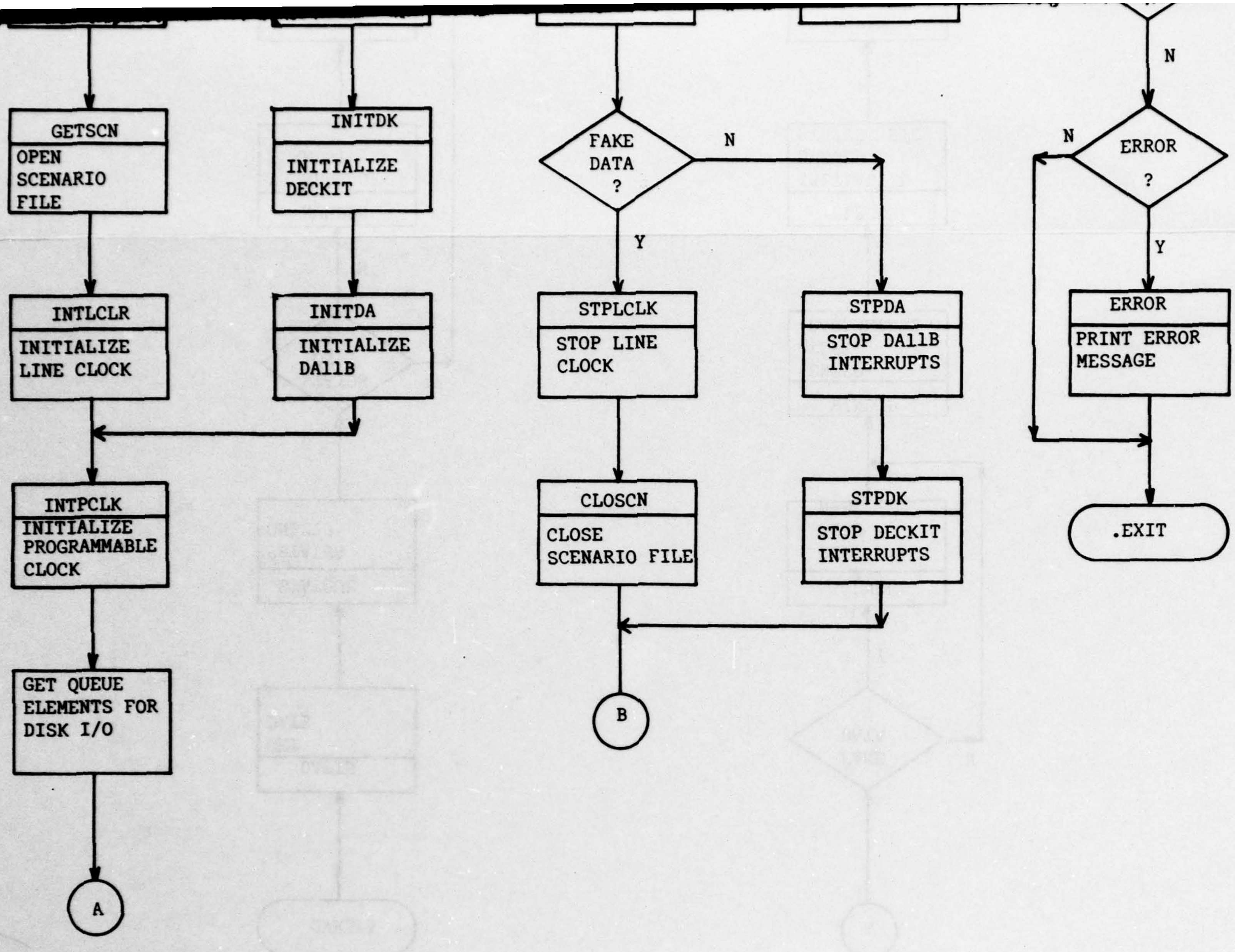
Chart 1

OVRLY1

2

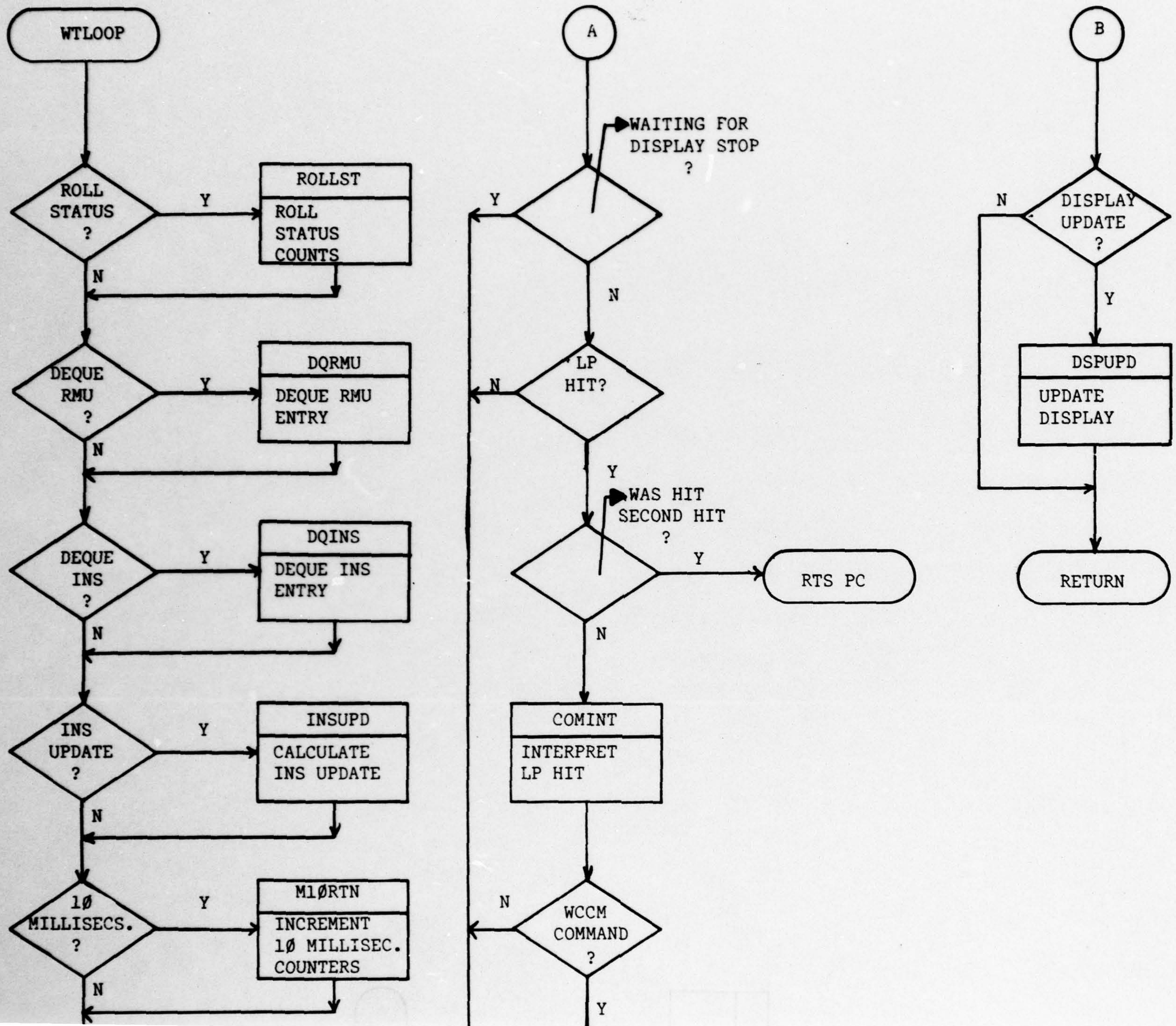


OVRLY2
GETCOM
READ COMMON BLOCKS
VTREST
RESTART DISPLAY
FAKE DATA ?
N
Y
SET UP FAKE INTERFACE ADDRESSES
SET UP REAL INTERFACE ADDRESSES
GETSCN
OPEN SCENARIO FILE
INITDK
INITIALIZE DECKIT
A
WTLOOP
TEST EVENT FLAGS
EXIT OR RESTART ?
N
Y
PCLKSTP
STOP PROGRAMMABLE CLOCK
BG3
CLEAR COMMAND
FAKE DATA ?
N
Y
CHAIN TO OVERLY1
B
DATA RECORDING ?
N
Y
CRECRD
CLOSE DATA FILE
VTGT
STOP DISPLAY
RESTART ?
Y
N
ERROR ?
N
Y



2

Chart 2
OVRLY2


WTLOOP
ROLL STATUS ?
Y
ROLLST
ROLL STATUS COUNTS
N
DEQUE RMU ?
Y
DQRMU
DEQUE RMU ENTRY
N
DEQUE INS ?
Y
DQINS
DEQUE INS ENTRY
N
INS UPDATE ?
Y
INSUPD
CALCULATE INS UPDATE
N
1Ø MILLISECS. ?
Y
M1ØRTN
INCREMENT 1Ø MILLISEC. COUNTERS
N
A
WAITING FOR DISPLAY STOP ?
Y
N
LP HIT?
N
Y
WAS HIT SECOND HIT ?
Y
RTS PC
N
COMINT
INTERPRET LP HIT
WCCM COMMAND ?
N
Y
B
DISPLAY UPDATE ?
N
Y
DSPUPD
UPDATE DISPLAY
RETURN

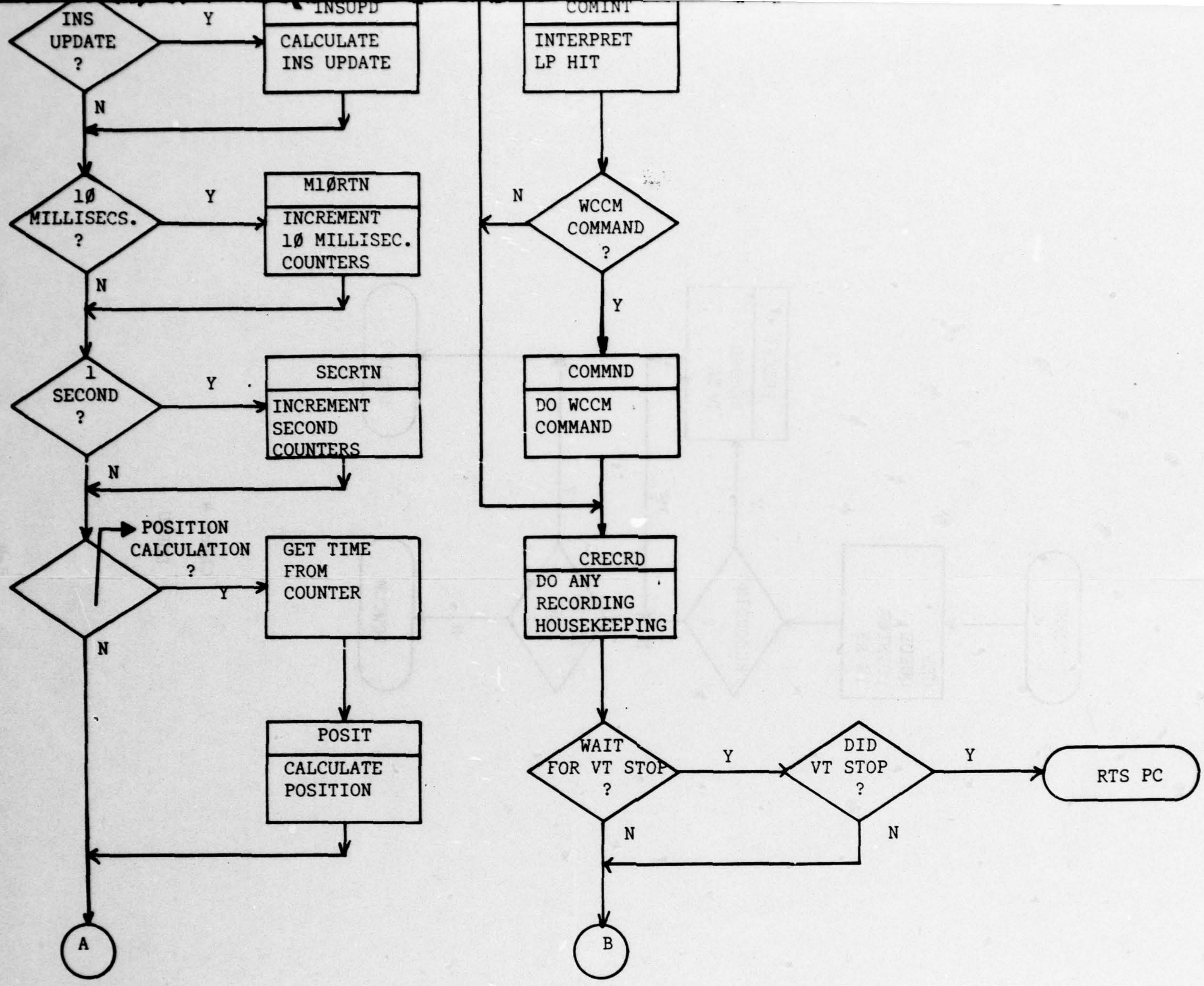


Chart 3

WTLOOP

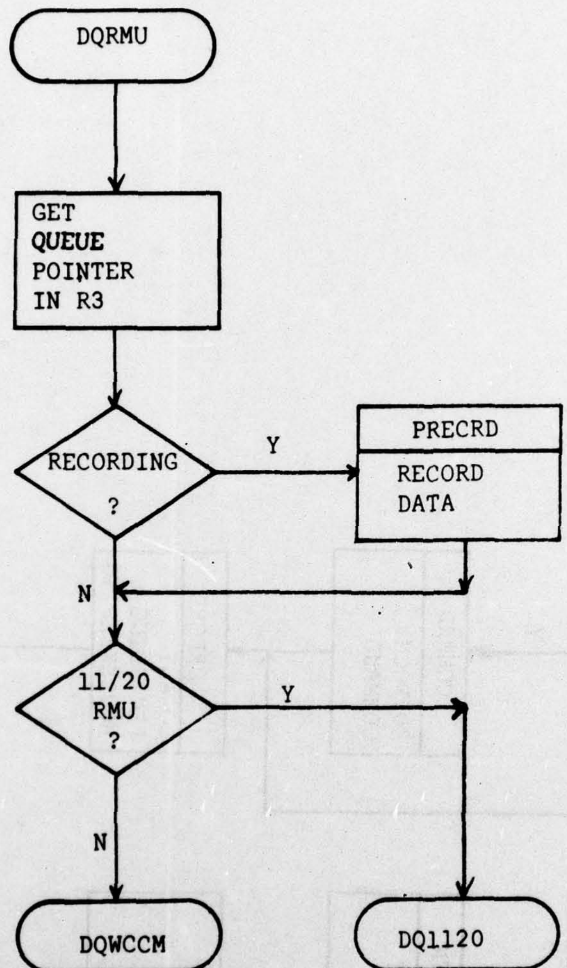


Chart 4

DQRMU

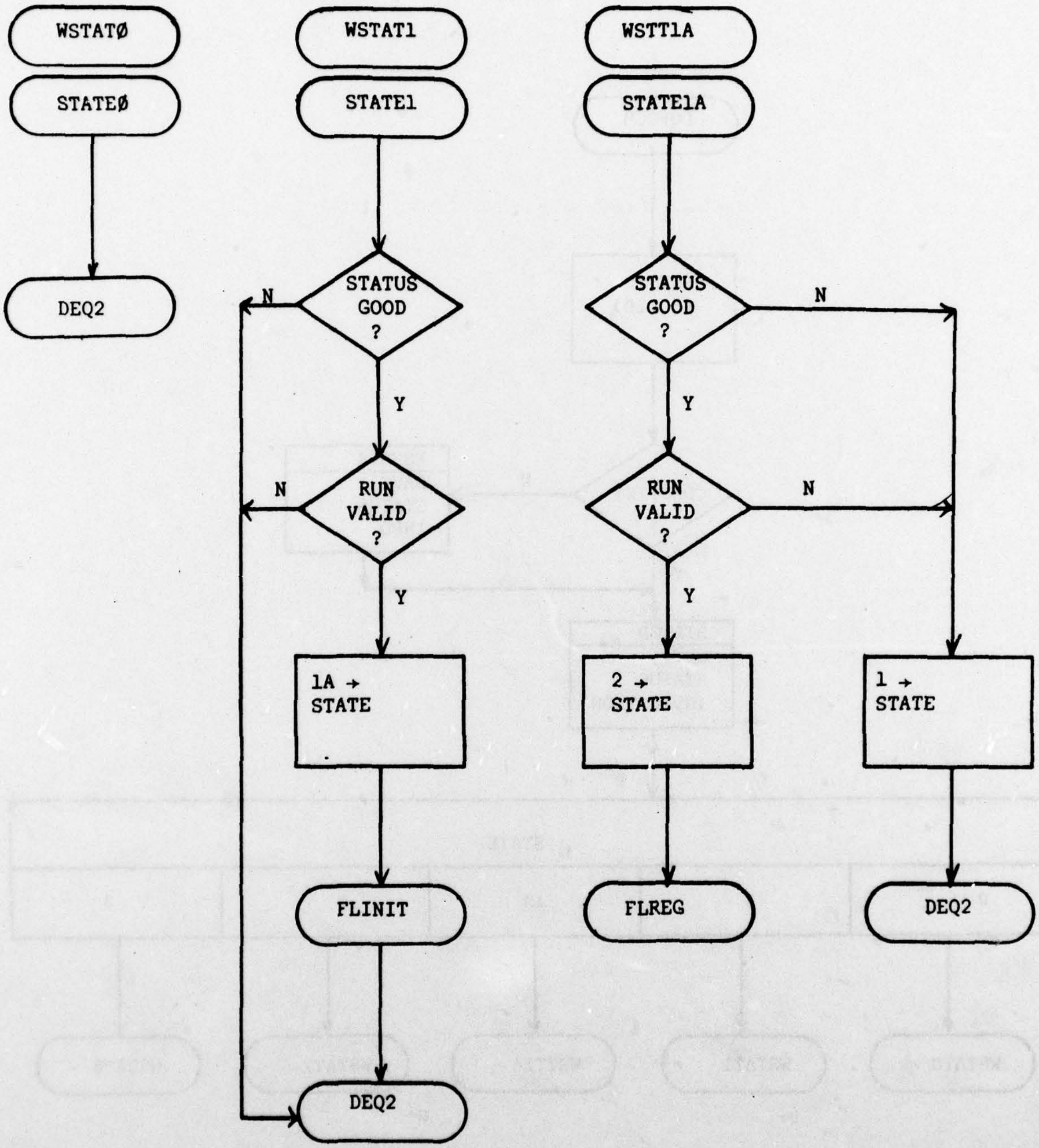


Chart 7

STATE 0, 1, 1A

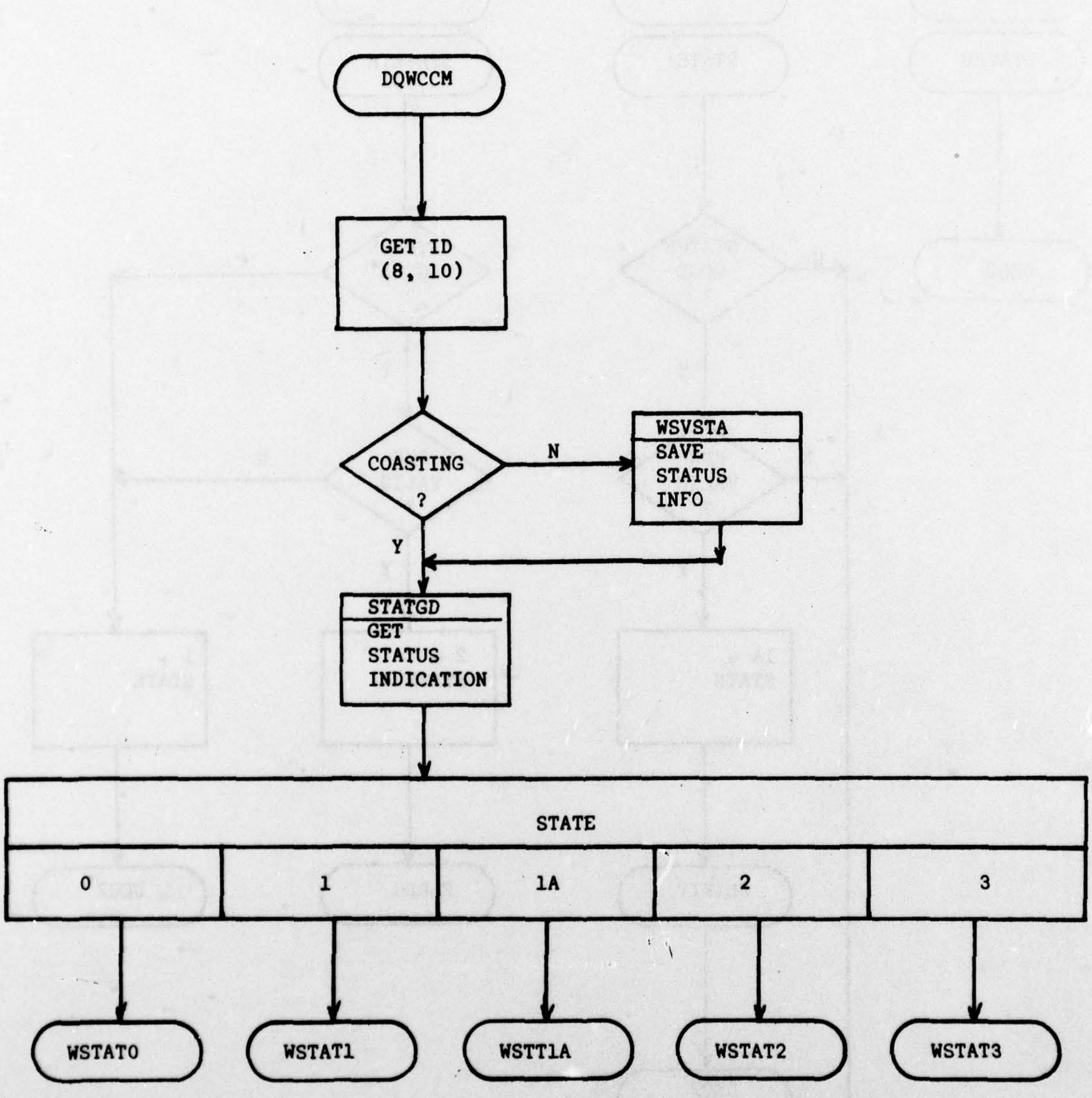


Chart 5

DQWCCM

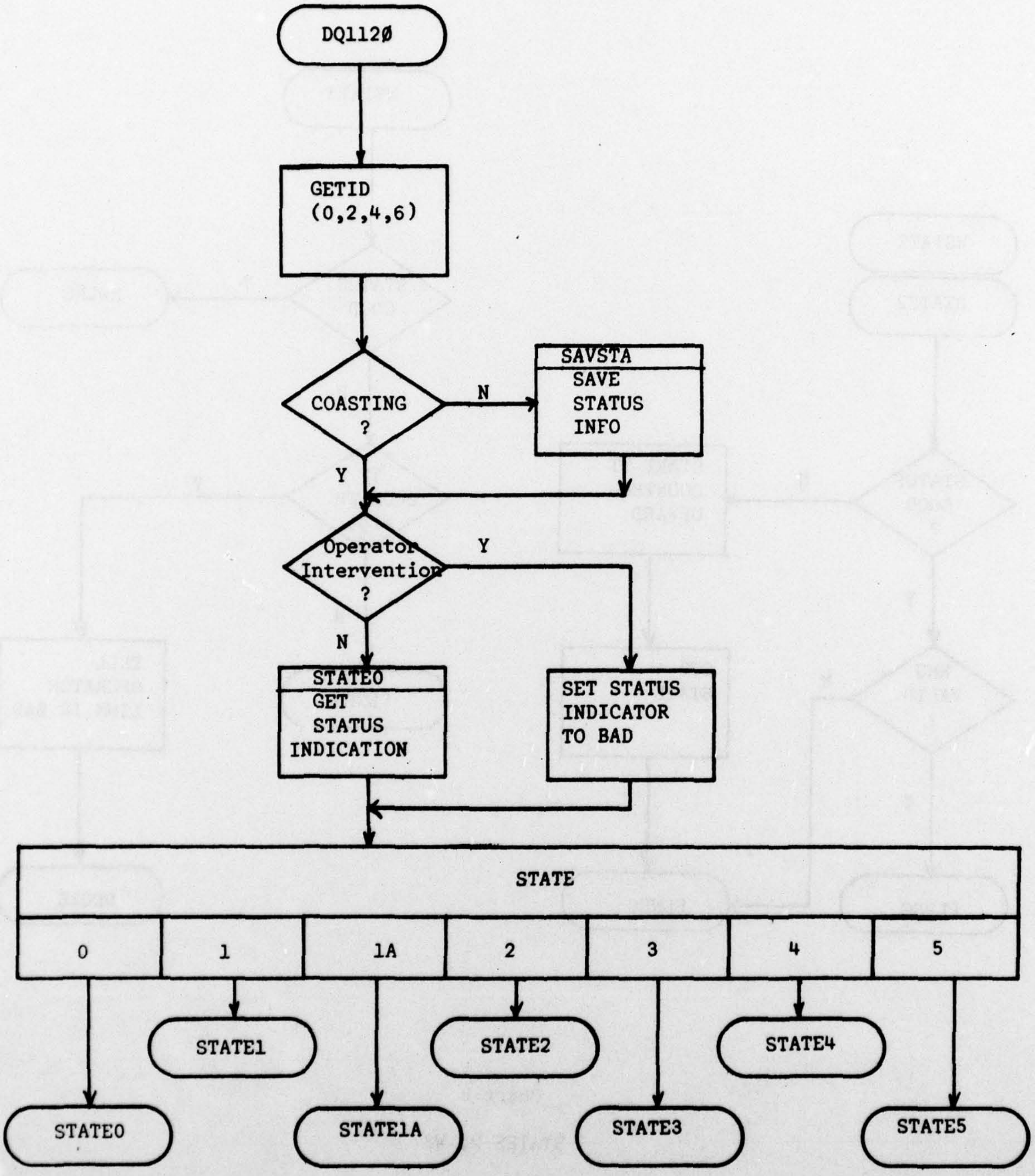


Chart 6

DQ112Ø

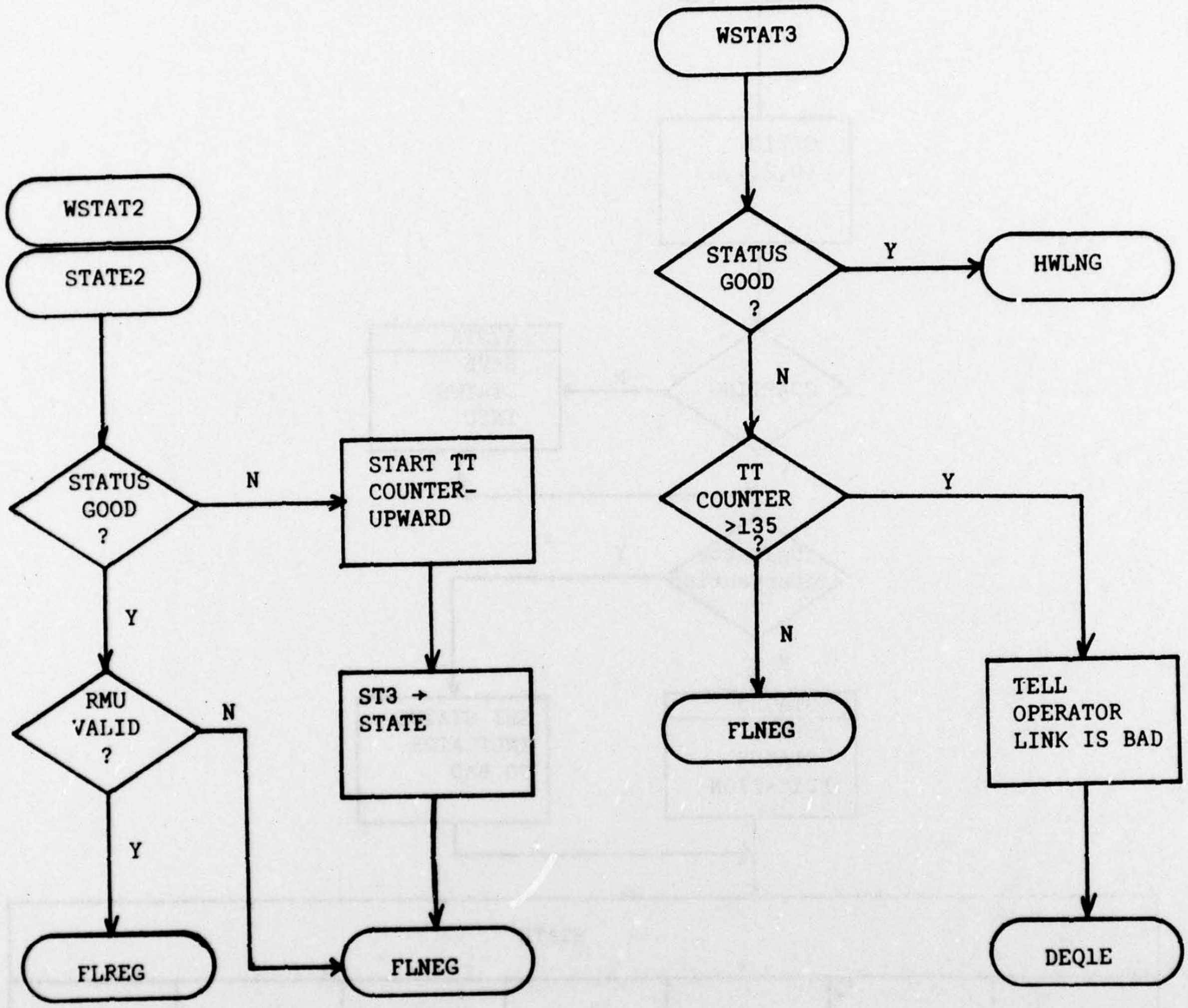


Chart 8

STATES 2, W3

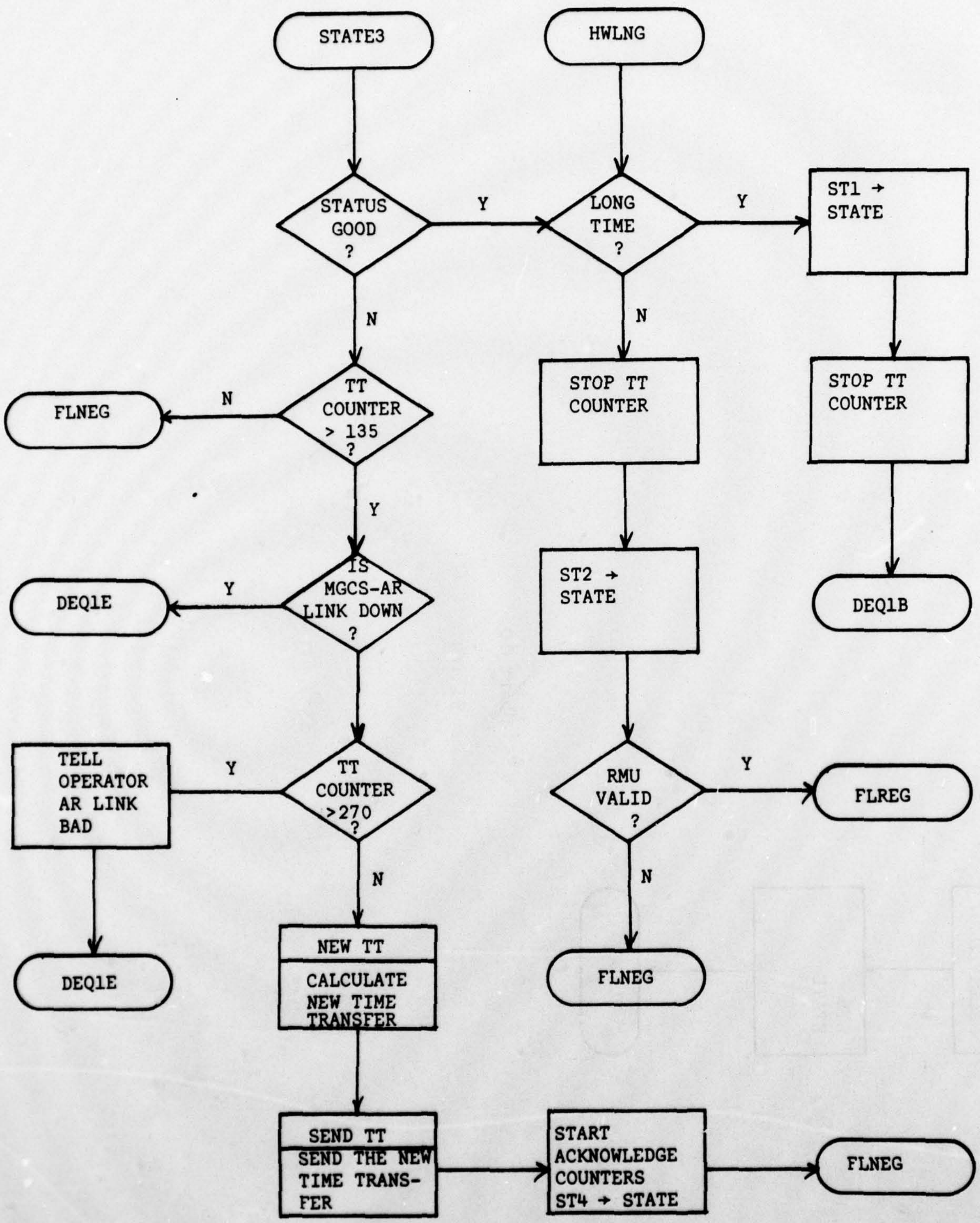
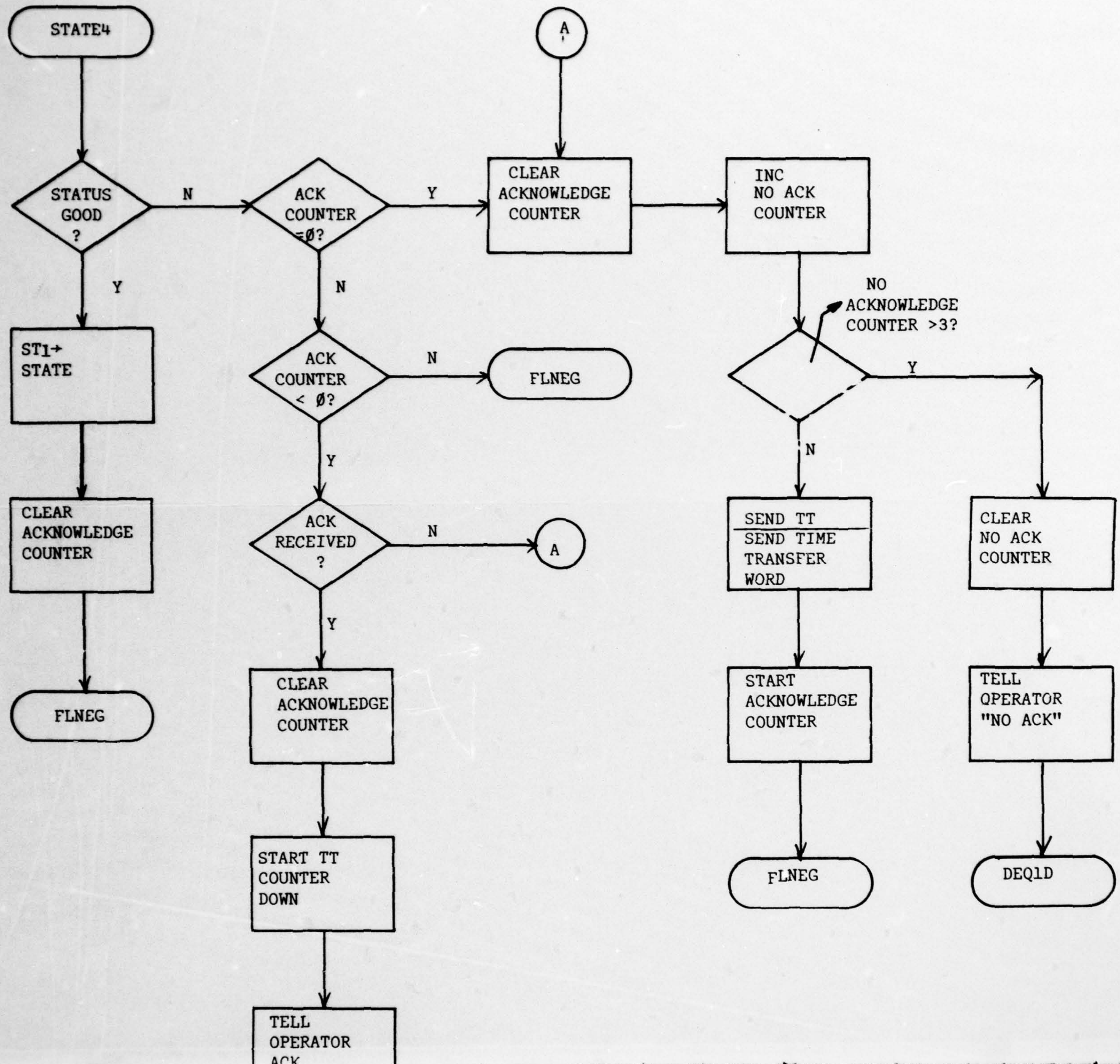


Chart 9

STATE3


STATE4
STATUS GOOD ?
N
Y
ST1→ STATE
CLEAR ACKNOWLEDGE COUNTER
FLNEG
ACK COUNTER =Ø?
Y
N
ACK COUNTER < Ø?
N
FLNEG
Y
ACK RECEIVED ?
N
A
Y
CLEAR ACKNOWLEDGE COUNTER
START TT COUNTER DOWN
TELL OPERATOR ACK
A
CLEAR ACKNOWLEDGE COUNTER
INC NO ACK COUNTER
NO ACKNOWLEDGE COUNTER >3?
Y
N
SEND TT
SEND TIME TRANSFER WORD
START ACKNOWLEDGE COUNTER
FLNEG
CLEAR NO ACK COUNTER
TELL QPERATOR "NO ACK"
DEQ1D

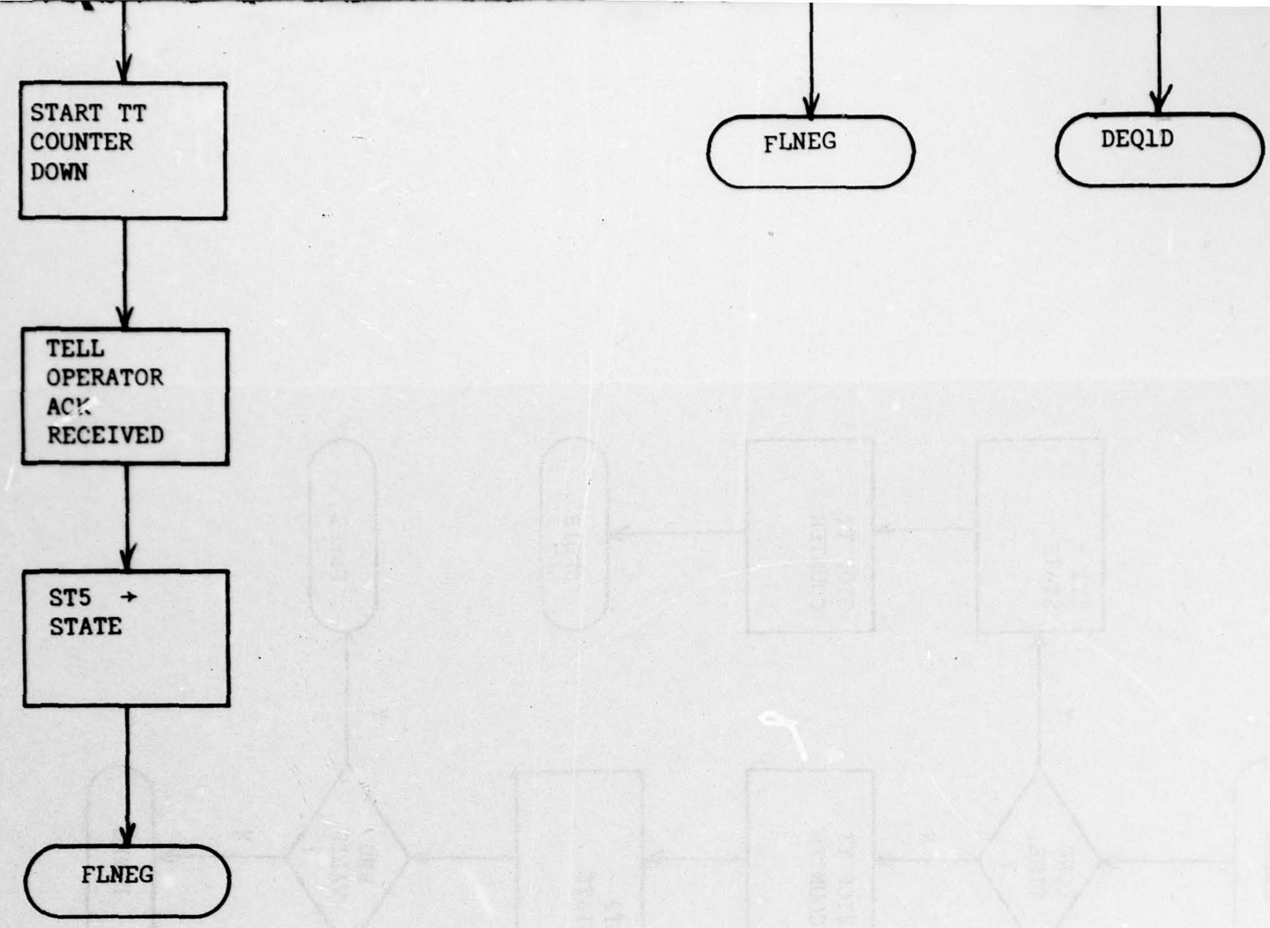


Chart 10

STATE4

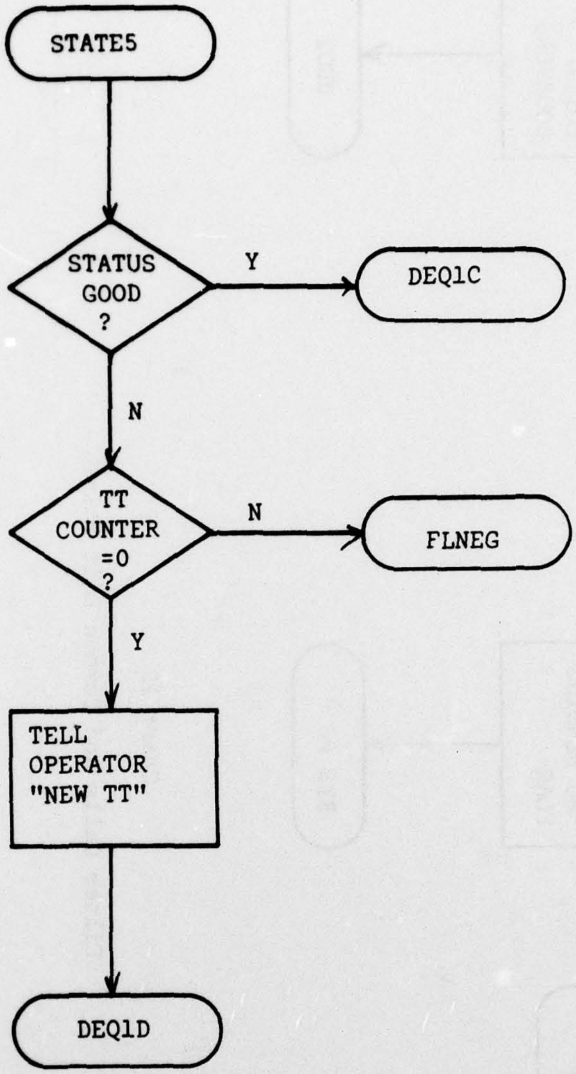
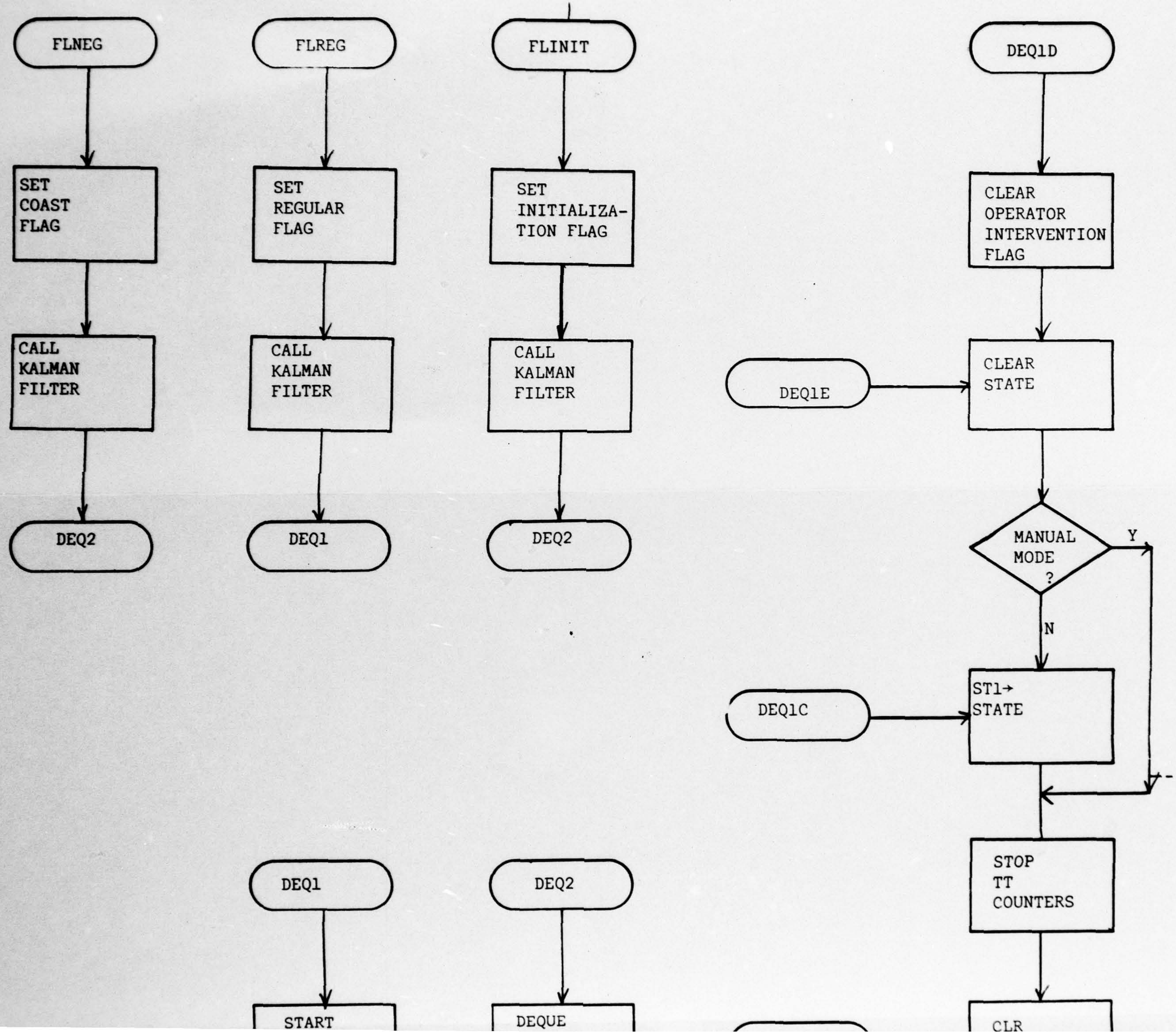


Chart 11

STATE5


FLNEG
SET COAST FLAG
CALL KALMAN FILTER
DEQ2
FLREG
SET REGULAR FLAG
CALL KALMAN FILTER
DEQ1
FLINIT
SET INITIALIZA-TION FLAG
CALL KALMAN FILTER
DEQ2
DEQ1D
CLEAR OPERATOR INTERVENTION FLAG
DEQ1E
CLEAR STATE
MANUAL MODE ?
Y
N
DEQ1C
ST1→ STATE
STOP TT COUNTERS
CLR
DEQ1
START
DEQ2
DEQUE

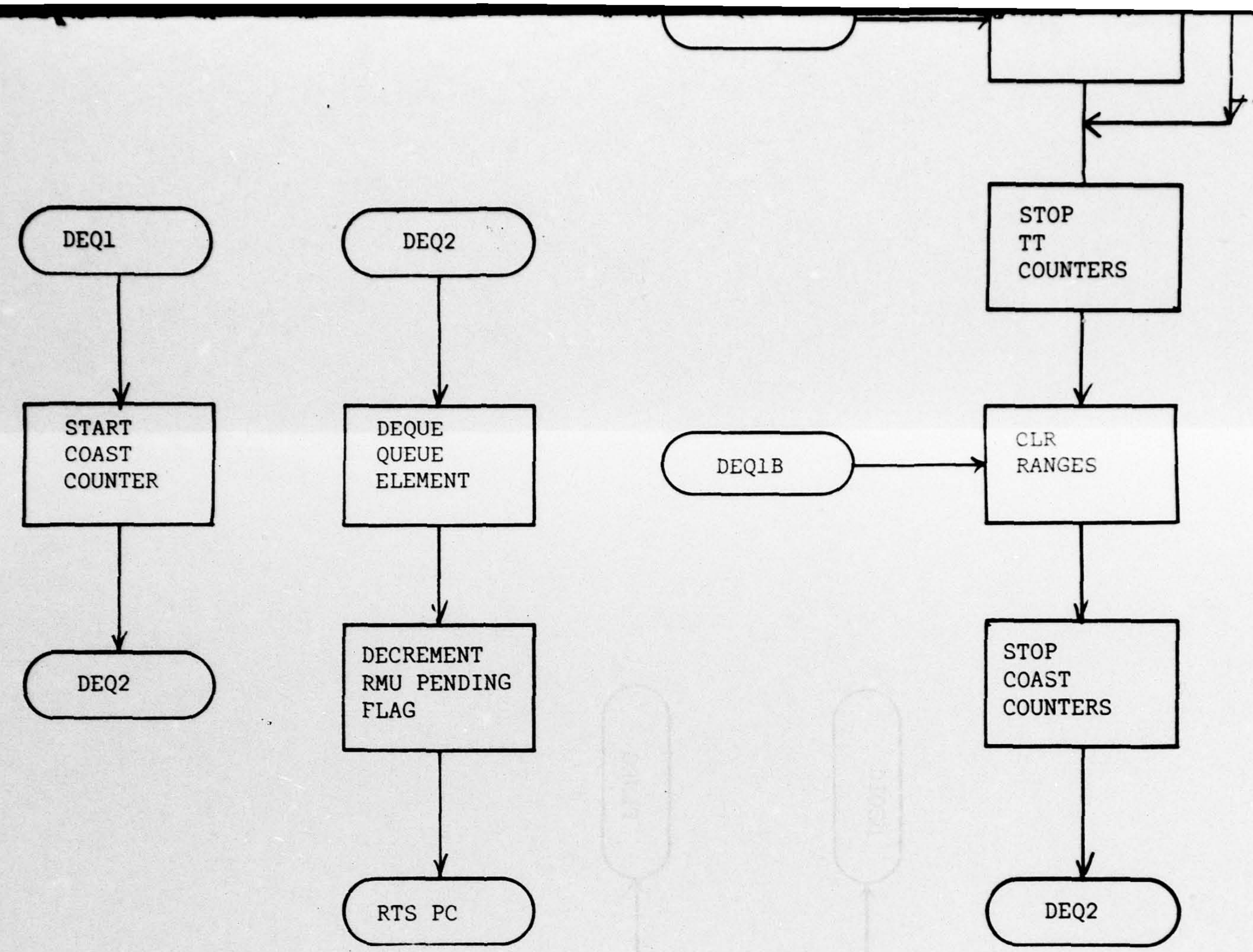


Chart 12

Filter Calls and Common Exit Points

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